

EFFECTS OF EL NIÑO/SOUTHERN OSCILLATION ON MEAN MONTHLY
STREAMFLOWS IN FLORIDA

By

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To my children, Anna Marie and Liana, so that they may recognize the inherent value of dedication and hard work to attain their goals in life, and to my wife, Mary, who has patiently endured and continually supported my academic pursuits.

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The representation and quantification of the effects of the El Niño/Southern Oscillation (ENSO) upon mean monthly streamflows and their spatial variabilities across Florida are the general objectives of this research. Thirty-three gaging stations, with periods of record between 30-67 years, are selected. Four parent probability distributions are tested for their efficacy in modeling the flows at-a-station and the parameters of the selected distribution are spatially modeled via trend surface analyses under warm (El Niño), cold (La Niña) and non-ENSO climatic conditions.

The lognormal probability distribution successfully represents the range of runoffs during each of the climatic conditions and, in a mixture model, their combination.

Parameters of the distribution are modeled successfully via second order trend surfaces which account for much of the spatial variation in both means and standard deviations, particularly during winter.

Results indicate that Florida streamflow responds in fairly complex ways to ENSO, largely due to its peninsular nature. Previously unidentified contrasts between the panhandle, northcentral and southern regions occur between ENSO conditions, marked by variations between winter and summer months. The analysis demonstrates that, during winter mean streamflow is significantly different between warm and cold events throughout the peninsula, but similar across the panhandle, unlike the response proposed in the literature. No summer relationship had previously been identified in the literature; however, this research indicates that the panhandle experiences below/above average streamflow during warm/cold events. Differences in the variances of flow are most pronounced in the south at the outset of summer with a spatial shift northward as the season progresses.

CHAPTER 1 INTRODUCTION

A great deal of hydrologic research has been devoted to the representation and quantification of the variability or stochastic properties of streamflow. In large measure this is due to the considerable practical importance of such endeavors. For example, engineering design and construction decisions are based upon predicted streamflows associated with specific recurrence intervals such as the 50- or 100-year floods (Yevjevich 1976; Rao 1986). Land use management decisions involving water resources are frequently based upon prediction of water volumes, levels and availabilities (O'Brien and Motts 1980; Tobin 1986). Diminishing fresh water reserves in the Tampa metropolitan area have resulted in debate over the construction of a pipeline by which to import water from the Suwannee river. Government and private agencies involved in emergency planning require knowledge of existing floodplains, the boundaries of which are based upon stochastic analyses of river discharge (Belt, Jr. 1975; Larson 1986). Thus, there is a need to make probabilistic statements (predictions) about likely

variations in streamflow and a great deal of effort has gone into improving such methods.

Justification

Recently there has been an increased interest in linking the numerical measures of variability to larger scale climatic variation such as the El Niño/Southern Oscillation (ENSO) to demonstrate the importance that this climatic state has upon regional precipitation events and consequent river discharges (Waylen and Caviades 1986; Caviades and Waylen 1991; Cayan and Webb 1992; Mechoso and Iribarren 1992; Richards 1995; Eltahir 1996; Trenberth and Guillemot 1996; Zorn and Waylen 1997). Yarnal and Kiladis (1985) characterize El Niño events as large-scale warmings of the generally cold eastern tropical Pacific Ocean, which are coupled with a large-scale "see-saw" of atmospheric pressure between the eastern and western tropical Pacific - the Southern Oscillation (SO). Sea level atmospheric pressure differences between Tahiti in the central Pacific and Darwin in northern Australia represent the state of the tropical Pacific climate. So strong is this relationship that a standardized measure of these pressure differences, known as the Southern Oscillation Index (SOI), is used as an indicator by which to assess the relative strengths of ENSO

events (Yarnal and Diaz 1986; Ropelewski and Jones 1987; Kiladis and Diaz 1989). The SOI signal tends to reveal moderate and stronger episodes of ENSO (Ropelewski and Halpert 1989).

Climatic anomalies which appear to be related but that occur at great distances from each other are known as teleconnections (Glantz 1984). The ENSO climatic anomaly has many linkages or teleconnections both within the tropics and in extratropical regions. For example, during El Niño events the Indian subcontinent and islands of Indonesia tend to experience disruptions in the summer monsoonal wind flows which lead to drought conditions (Enfield 1987; Ropelewski and Halpert 1987). Southern Africa also tends to demonstrate a strong teleconnection with the tropical South Pacific. Extratropical regions that have teleconnections with ENSO include northwestern and southeastern North America. In terms of temperature the northwest exhibits warm winter anomalies whereas the southeast exhibits cool winter anomalies (Kiladis and Diaz 1989). Although the response is more complex, precipitation and streamflow teleconnections with the tropical Pacific exist in each of these regions (Ropelewski and Halpert 1986, 1989; Kahya and Dracup 1993a; Henderson and Robinson 1994).

Florida lies within this southeastern region. However, meteorologic and hydrologic processes vary substantially

across the state between seasons. The panhandle typically experiences a winter maximum in streamflow generated primarily from frontal systems, and the proportion of annual streamflow occurring during the season decreases toward the south. Conversely, the southern region of the peninsula experiences a strong summer maximum in streamflow generated from convectional and tropical storms. The summer proportion of annual streamflow decreases northward. Because of these temporal and spatial differences in hydrometeorologic processes across the state, it is hypothesized that Florida will not respond to ENSO conditions in a consistent manner as described for the southeastern region in the literature.

Objectives

The general objective of this dissertation is to probabilistically characterize the interannual variability of monthly mean streamflows of rivers in Florida in such a way as to assess the varying impacts of ENSO upon the hydroclimatic regime across the state. Meteorologic and hydrologic processes vary substantially across the state; therefore, it is reasonable to assume that responses to ENSO will also vary spatially. The details of such spatial variability will be of geographic interest in and of

themselves and, when modeled appropriately, may provide the basis for streamflow predictions at ungaged locations.

The effects of ENSO on mean monthly streamflow in Florida are characterized and documented based upon the following objectives: 1) determine those months in which streamflow is potentially influenced by conditions in the tropical South Pacific Ocean as represented by the SOI, 2) determine the underlying parent probability distributions of mean monthly streamflows at each station in light of the first objective, 3) investigate the spatial variability of the parameters of the requisite parent distributions in order to assess the influence of ENSO across Florida, 4) develop a spatial representation of parameter variability in order to assess the regional differences in the influence of ENSO and 5) test the efficacy of the procedure to adequately predict probability distributions of mean monthly flows at ungaged locations.

Structure of Presentation

A review of the literature is presented in Chapter 2. The general framework is established whereby this analysis is placed in the broader perspective of hydrologic and climatologic research. A description of the study area and data is provided in chapter 3. Methods by which the mean

monthly streamflows are modeled, both at-a-station and spatially across the study area, are detailed in chapter 4. Chapters 5 and 6 present the results of the at-a-station and spatial analyses, respectively. The spatial modeling of these results and the ability of these models to generate adequate predictions of underlying distributional form are detailed in chapter 7. Additional implications and directions of future research are presented in chapter 8 and, finally, chapter 9 is a summary of the more salient aspects of this dissertation.

CHAPTER 2 LITERATURE REVIEW

An overview of the El Niño/Southern Oscillation (ENSO) climatic anomaly and its characteristic phases is first presented, followed by a discussion of correlation analyses in regard to associations or teleconnections between the phenomenon and climatic perturbations in North America. Other works which have documented the teleconnections between the tropical South Pacific and hydrometeorologic patterns in the southeastern United States are also presented. The chapter concludes with reviews of the literature on probability distributions within the framework of flow-frequency investigations in hydrology and the problems of spatial analysis and prediction in both geographic and hydrologic terms.

El Niño/Southern Oscillation

General surface circulation throughout the tropical South Pacific Ocean consists of cold sea surface temperatures (SSTs) in the east due to upwelling waters, and warm sea surface temperatures in the west due to equatorial

warming of the waters that are directed westward by the SE Trade winds (Trenberth 1991). El Niño events, which are oceanic in nature, are characterized by warmer than normal SSTs throughout the eastern Pacific, caused in part by the relaxation of the SE Trade winds (Rasmusson 1984; Enfield 1987, 1989). Anti-El Niño (or La Niña) events occur when colder than normal temperatures exist in the eastern Pacific, complemented by warmer than normal conditions in the western sector (Philander 1985; Yarnal and Diaz 1986). Hence, El Niño events are also known as "warm events" and anti-El Niño events are referred to as "cold events." Terminology is used interchangeably (Aceituno 1992), but in this work the terms "warm" and "cold" will be applied.

Atmospheric pressure systems across the southern tropical Pacific are generally distributed spatially with a high pressure zone (South Pacific Anticyclone) over the eastern Pacific and a low pressure zone (Indonesian Low) over the western Pacific (van Loon and Madden 1981). These pressure cells are occasionally more marked than normal following warm events and they are then referred to as cold episodes (Philander 1985; Diaz and Kiladis 1992). During warm events, warm water propagating into the eastern Pacific reduces atmospheric pressure. Conversely, pressures are generally higher than normal in the western Pacific (Enfield 1989). Atmospheric pressure therefore tends to oscillate

across the southern tropical Pacific between two extreme states--warm and cold phases. This phenomenon is known as the Southern Oscillation (van Loon 1984; Philander 1992). Because the atmospheric and oceanic systems are now known to be inextricably linked or coupled, the large-scale events in which conditions are reversed throughout the tropical Pacific are referred to as warm El Niño/Southern Oscillation (ENSO) events (Rasmusson and Wallace 1983; Diaz and Kiladis 1992). Cold ENSO events occur when the "typical" condition is intensified, i.e., when colder (warmer) than normal waters exist in response to anomalously high (low) atmospheric pressure across the eastern (western) tropical Pacific Ocean (Philander 1985; Yarnal and Diaz 1986).

The term "El Niño" referred in the past to an annual, geographically limited, southward flowing warm current off the coast of Ecuador and northern Peru during austral summer; however, the term is now used to refer to a large-scale warming of the entire eastern tropical Pacific Ocean (Quinn et al. 1987). The former description is also a short-lasting phenomenon, on the order of a month or so, whereas the latter event can last for periods of one year and longer (Enfield 1989; Solow 1995). Owing to the spatial variability of the major variables (oceanic and atmospheric) involved in the ENSO phenomenon, as well as the varying time scales at which they operate, each ENSO event is unique

(Schonher and Nicholson 1989; Philander 1992). The geographic extent of anomalously warm sea surface temperatures in the eastern Pacific, for example, varies from event to event as does the magnitude of the anomalies (Cane 1983; Rasmusson and Wallace 1983). The warm event of 1972 lasted approximately eighteen months and was more intense than the warm event of 1976 which lasted over two years (Philander 1990). The magnitude of SO anomalies also varies from one event to another. Values of the nine month running mean of monthly sea level pressures at Tahiti in the central tropical Pacific are not as low for the 1941 ENSO event as they are for the 1982 event. Timings vary, as well (Diaz and Kiladis 1992).

Given the unique qualities of ENSO events, a composite approach, by which ENSO events are aggregated in order to establish average behavior of the variable of interest, has become a standard research approach (Rasmusson and Carpenter 1982). It has been used in regard to mean annual and seasonal values of variables such as SST and atmospheric circulation and they are shown to be correlated with sea level pressure at Darwin from 1950-1979 (Wright et al. 1988). Such an approach yields a correlation coefficient of 0.88 between sea level pressure at Darwin and central Pacific SSTs from July-November, suggesting that when pressure at Darwin increases (as it does during warm events)

there is the tendency for central Pacific SSTs to simultaneously increase. Teleconnections refer to similar significant correlations in atmospheric variables between locations separated by long distances (Yarnal and Kiladis 1985); thus, such a correlation indicates a teleconnection between SST in the central and eastern Pacific and pressure across the western Pacific. This teleconnection is best explained by atmospheric dynamical processes regarding the relationship between pressure, SST and Walker circulation (Wright 1985).

In order to examine the evolution and timing of ENSO events, composites of SST, atmospheric pressure, temperature and precipitation from both tropical and extratropical locations have also been developed (Rasmusson and Carpenter 1982; Rasmusson and Wallace 1983). Results indicate there is an onset phase of ENSO that begins in December of the year preceding the event (year -1) and a peak phase in April during the event (year 0) characterized by anomalously warm waters extending from the eastern Pacific in a narrow band across the equatorial region into the central Pacific (Rasmusson and Carpenter 1983; Enfield 1989). A mature phase, characterized by peak SSTs in the central and eastern Pacific during November-December, occurs in January of the year following the event (year +1), at which time teleconnections with the extratropics are strongest (Webster

1982; Yarnal 1985). Regarding the SO, the eastern Pacific is characterized by slightly higher than normal pressures during the onset phase, declining to below average pressures by August during the event year (Rasmusson and Wallace 1983).

Correlation Analyses

Working in the 1920s, Sir Gilbert Walker was the first to identify the inverse correlation or teleconnection between atmospheric pressure among the western and eastern tropical South Pacific regions (Enfield 1989; Diaz and Kiladis 1992). Jacob Bjerknes (1966) used the new satellite imagery of the 1960s to establish the links between atmospheric and oceanic circulation, showing that changes in one can induce changes in the other. Furthermore, he noted the tendency for northern hemisphere atmospheric circulation patterns to shift during ENSO events. Since then, several works have documented the association between boreal circulation patterns and conditions in the tropical Pacific in addition to the effects these patterns have on the spatial distributions of temperature, precipitation and river discharge across North America (Namias 1969; Wyrtki 1973; Horel and Wallace 1981; Ropelewski and Halpert 1986; Leathers et al. 1991; Kahya and Dracup 1993a, 1994). Many

of these teleconnections have been established on the basis of correlation analysis.

Since the SO is a persistent phenomenon, exhibiting the tendency to remain positive or negative over extended periods with a high interannual variability, simultaneous and lag correlation analyses are used extensively in teleconnections research (Ramage 1983; Wright 1985). These studies have served to establish aspects of the Southern Oscillation such as its large-scale coverage, seasonal variations and lag associations with related climatic variables (Nicholls 1987; Trenberth and Shea 1987). For example, in the tropical South Pacific the SO signal dominates the variability in sea surface temperature and atmospheric pressure. Correlations between the SO and SST vary seasonally as they tend to be strongest in late fall and weakest in early spring (Wright 1985).

The presence of autocorrelation in the time series of many monthly measures of climatic variables presents problems which may lead to apparent leading or lagging relationships when none is actually present (Brown and Katz 1991). For example, climatic and oceanic time series generally possess substantial autocorrelation in the form of positive dependence, reflecting their tendencies to persist over time. The reliability of the resulting cross correlation coefficients is therefore reduced. For example,

month to month autocorrelations among Darwin pressure, SST and rainfall in the central tropical Pacific are strongest from July-November, the period at which these variables demonstrate the strongest correlations with the SO (Wright et al. 1988). Although a significant relationship may still be present, the strength of the relationships must be less than that calculated without correcting for the effects of autocorrelation (Brown and Katz 1991).

Teleconnections to North America and the Southeastern U.S.

The nature of teleconnections between conditions in the tropical Pacific and precipitation and temperature regions of North America is fairly well-established. For example, correlation between the SO and subsequent winter precipitation in the southeast U.S. has been known for over sixty years (Enfield 1989) although the mechanisms responsible for the relationship have only recently become apparent (Namias and Cayan 1984; Ropelewski and Halpert 1986; Kiladis and Diaz 1989). The month of maximum response in precipitation to ENSO in the southeast U.S. has been determined to be December of the ENSO year (year 0) through the use of a 24-month harmonic analysis (Ropelewski and Halpert 1986, 1989). When streamflow data are subjected to the same type of analysis, maximum response in discharge is

found to occur in March of the year following an ENSO event (year +1) due to the lag effect of storage (Jordan 1984; Kahya and Dracup 1993b, 1994). A problem with this approach is the assumption of a single peak response to ENSO forcing which may not hold true for the more complex hydrologic regimes of Florida.

During warm event years the equatorial Pacific zone of convective activity, normally present in the western region of Indonesia, shifts eastward into the central equatorial region in conjunction with the negative phase of the Southern Oscillation (Rasmusson and Carpenter 1982; Rasmusson and Wallace 1983; Enfield 1989). Jet stream patterns are perturbed to more amplified, meridional paths and the subtropical jet emanates out of a trough in the tropical Pacific accounting for the advection of moisture into the southeast United States (Rasmusson and Wallace 1983; Lau and Lim 1984; Emery and Hamilton 1985; Yarnal 1985). A positive correlation (0.60) between autumnal precipitation in the central equatorial Pacific and subsequent winter (Dec.-Feb) precipitation in Florida has been substantiated (Douglas and Englehart 1981). Furthermore, the largest positive rainfall anomalies occur throughout the state during winter and spring following an El Niño event (Hanson and Maul 1991). There is a statistically significant relationship (0.01 level) between

the moisture condition (represented by Palmer's Drought Severity Index or PDSI) across Florida and the SOI during winter (Yin 1994). Teleconnections, therefore, are such that during warm event years, when the zone of convection and precipitation is located in the central equatorial region, Florida tends to receive above normal winter precipitation. Conversely, Florida generally receives below average winter rainfall when the zone of convection is displaced westward (Ropelewski and Halpert 1989; Henderson and Robinson 1994).

Tropical storm development throughout the North Atlantic Ocean basin is also affected by the shifting region of convection (Gray 1984b; Reading 1990; Caviades 1991; Vega and Binkley 1991). During warm (cold) years the number of tropical storms is generally below (above) average (Gray 1984a). Although these analyses apply to the entire North Atlantic region, it is reasonable to expect similar responses in summer precipitation and subsequent river discharge in Florida, especially in those areas most prone to receiving moisture from tropical systems during the tropical storm "season" of June-November. Effects of ENSO on precipitation generated from these storms are most likely experienced during the period of highest frequency from mid-August through mid-October (Neumann et al. 1987; Waylen 1991).

Precipitation is generally below average during warm event summers (June-September) across the southeastern U.S. and above average during cold event summers (Henderson and Robinson 1994). Northern Florida, particularly the panhandle, tends to receive below average summer (June, July, August) precipitation during warm events and the entire peninsular portion of the state receives below average precipitation in the subsequent autumn (September, October, November). Only the panhandle experiences above average rainfall in the fall (Hanson and Maul 1991). Not only does the response in mean monthly streamflow mirror this pattern, but the variability in flow is statistically different between warm and cold years during the summer in northcentral Florida (Zorn and Waylen 1997). In terms of the PDSI, moisture conditions are frequently out of phase with the other southeastern states, indicating that Florida may not be correctly classified when grouped within the entire southeast region (Henry and Dicks 1988; Henry and LeBoutillier 1990). ENSO events also appear to be related more closely to the moisture condition of Florida than to the remainder of the southeast. The summer relationship suggests that most of the state experiences normal moisture conditions during warm event summers but that the entire peninsular region is drier than normal during cold event summers (Yin 1994). However, there is also contradictory

evidence which indicates that mean summer precipitation (July, August, September) is greater during warm years than cold years across the southern U.S., although not statistically significant, and that autumnal (October, November, December) precipitation is significantly greater during warm years (Rogers 1988).

Although teleconnections between ENSO and various hydrometeorologic variables for the southeast U.S. have been substantiated, exact agreement regarding their spatial and temporal characteristics does not exist. For example, Florida may be incorrectly classified within the southeast region as a whole (Ropelewski and Halpert 1986, 1989; Henry and LeBoutillier 1990; Kahya and Dracup 1993a,c) and some studies operate on a seasonal time scale (Rogers 1988; Hanson and Maul 1991) while others are performed at the monthly time scale (Yin 1994). Therefore, a probabilistic technique can serve to alleviate some of these discrepancies by simply characterizing monthly streamflows in terms of chance, given the occurrence of warm or cold events.

Theoretical Probability Distributions

A probabilistic approach to hydrologic analysis gives rise to models that represent the salient features of the hydrologic variable (e.g. monthly streamflows), which

generally include the mean and variance, and other statistical measures which may be desirable, depending on the distribution in question. The approach characterizes particular values of a hydrologic variable in terms of its chance or potential likelihood, via probability distributions. Frequency curves relate magnitudes of continuous hydrologic variables to their frequencies of occurrence as either probability density curves or in their cumulative forms as cumulative probability distributions (Riggs 1968).

Desirable characteristics of the selected probability distribution include 1) good fit to the empirical data, 2) a theoretical basis for its application to the problem at hand, 3) easily interpretable parameters, 4) parsimony in the number of parameters employed, and 5) that the distribution may be appropriate to each of the sampling locations. In reality it is difficult to satisfy each of the requirements; therefore, a balance among them is generally the optimal solution. A widely used continuous probability distribution in inferential statistics is the normal or Gaussian distribution because of its mathematical property regarding the central limit theorem, which concerns the approximate normality of means of random samples or of sums of random variables (Haack 1979). Central limit theorem states that regardless of the parent distribution of

the population, the distribution of the sample mean is approximately normal if the sample size is large, permitting the use of standard tests of differences between means and variances (Huntsberger and Billingsley 1987; Griffith and Amrhein 1991). In general, a minimum sample size of 30 is required for continuous data (Haack 1979; Burt and Barber 1996). Non-negative variables, such as streamflow, cannot be strictly normally distributed because they are bound with a lower limit of zero. However, the lognormal distribution is derived from normal theory and the central limit theorem in that the natural logarithms of the hydrologic variable may be expected to be normally distributed (Haan 1977).

Previous research suggests that monthly and seasonal aggregations of streamflow and precipitation generally follow a lognormal distribution, although exceptions exist, particularly with large rivers (Harms and Campbell 1967; Moreau and Pyatt 1970; Singh and Lonquist 1974; Stedinger 1980; Bras et al. 1983; Richards 1995; Eltahir 1996; Guetter and Georgakakos 1996). Alternate choices include the gamma distribution, which has an empirical basis for its application to monthly and annual streamflow, especially when the data show pronounced skewness of either the flows or their logarithms (Singh and Lonquist 1974). The Weibull distribution, derived from extreme value theory, has also been used to model seasonal precipitation in Florida because

of its ability to fit skewed data (Richards 1995). Finally, on any single river more than one applicable distribution may be appropriate as the seasons change. For example, Bras et al. (1983) found that monthly streamflow of the lower Nile is best modeled by the lognormal distribution for five months and the normal distribution for the remaining seven months.

Understanding the temporal and spatial aspects of the physical processes that affect frequency characteristics is essential to the development of accurate models (Potter 1987; Conway and Hulme 1993; Trenberth and Guillemot 1996). The mixed distribution model, such as that proposed by Singh and Sinclair (1972), has been used to account for seasonal differences in the generating mechanisms of precipitation and streamflow (Elliott et al. 1982; Diehl and Potter 1986; Hirschboeck 1986; Webb and Betancourt 1992). This model has been shown to better represent monthly streamflows in Illinois than common theoretical distributions because the frequencies with which the generating mechanisms (spring snowmelt and summer rainfall) occur serve as weights for each component distribution. Although the data are lognormally distributed for some of the drier months with higher positive skew, the mixed lognormal satisfactorily models those which are not (Singh and Lonquist 1974).

Mean monthly discharges for the Santa Fe river at Worthington Springs, Florida (Zorn and Waylen 1997) do not appear to follow a lognormal distribution; rather, they tend to be "S"-shaped (figure 2.1). Singh and Lonquist (1974) suggest that such curves are the result of more than one generating mechanism. This is not completely unexpected since it has been shown that, in Florida, precipitation and streamflow result from several distinct processes, including frontal convergence, non-frontal convergence (tropical systems) and convection (Jordan 1984). Monthly streamflows might then be modeled successfully via the mixed lognormal distribution using warm, cold and non-ENSO years as sub-classifications for each component probability distribution.

Spatial Distribution of Model Parameters

Predictions of the distributions of streamflow are often needed at locations where data are either absent, insufficient or subject to sampling errors. However, adequate records may be available for neighboring rivers or locations. In addition, the data from a single location constitutes a random sample from a population described by an unknown probability distribution with uncertain parameters. Thus, the variability inherent in this type of

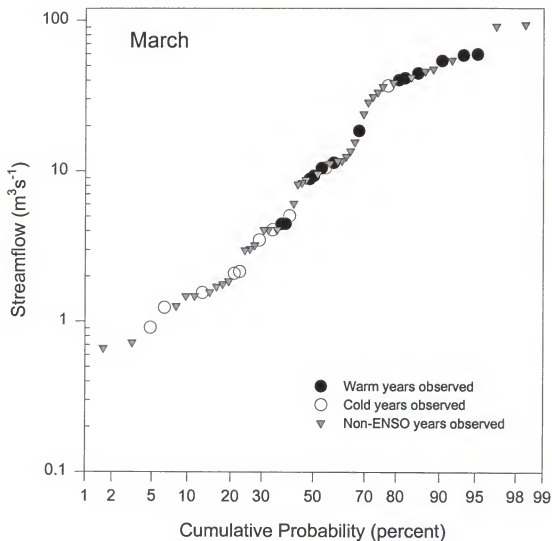


Figure 2.1 Mean monthly streamflows for the Santa Fe river at Worthington Springs.

random sample renders a consideration of regional frequency analysis more appropriate (Haan 1977; Wiltshire 1986).

Streamflow is an integrated output from all the processes operating within a given drainage basin. Larger basins generally experience greater absolute volumes of precipitation and have larger groundwater reservoirs than do smaller basins (Jordan 1984). Due to these natural inequalities, hydrologic analyses must account for differences in behavior resulting from basin area and direct comparison between large and small basins must be avoided (Klemeš 1983). Larger basins tend to have higher mean flows but lower values of skewness and variance. In addition, the presence of large percentages of area occupied by other hydrologic stores, such as lakes, induces a more even distribution and moderate range of streamflows (Singh 1992). A suitable technique for standardizing flows from drainage basins of varying size is to divide discharge by drainage area, resulting in specific runoff, a measure of flow expressed in units of volume per unit time per unit area (Smith 1989). This allows comparisons to be made between large and small basins, although this is probably only true within specific ranges.

Trend Surface Analyses

One approach to modeling the spatial variability in hydrologic parameters is that of continuous mapping. The technique is applicable when responses in streamflow vary smoothly and predictably across space, and it entails modeling the variability in parameters continuously across space via trend surface analysis, a specific form of multiple regression (Marsal 1987).

Trend surface analyses (Unwin 1975; Woo and Waylen 1984; Kutiel 1987) and multiple regression (Parrett and Cartier 1989; Rankl et al. 1994) have been employed to assess the variation in model parameters of regional frequency distributions. In order to predict the values of the parameters at ungaged locations, estimates of surface coefficients, basin location and, if necessary, other basin variables are required (Unwin 1975).

Remarks

Characteristics of the El Niño/Southern Oscillation (ENSO) climatic anomaly and its phases have been presented within this chapter. Winter precipitation and streamflow in Florida responds to ENSO in the season following events whereas the summer response is simultaneous with the event. Much of the research on teleconnections has been performed

using correlation analysis, which is limited in that no measure of variability is derived from these works. Therefore, an overview of the literature on probability distributions, by which measures of both mean and variation are assessed, within the framework of flow-frequency investigations in hydrology is presented. Finally, the problems of spatial analysis and prediction in both geographic and hydrologic terms have been addressed.

CHAPTER 3 STUDY AREA AND DATA

A simple water balance approach is employed in this chapter in order to structure the discussion of the complex spatial and temporal variability of monthly discharge over the study area. The hydrologic budget of a drainage basin over a particular time period is expressed by Singh (1992) as follows: $I = O \pm \Delta S$, where I is input, O is output and ΔS is change in storage. In Florida inputs result almost entirely from precipitation (P) in the form of rain, although groundwater transfers from other basins may be significant. Outputs are generally runoff (R), evaporation (E), and losses to inter-basin transfers of groundwater. Significant hydrologic stores operating with residence times of one month may include large lakes and regional groundwater. Thus, the equation can be re-formulated as $R = (P - E) \pm \Delta S$. This chapter outlines the spatial and temporal variability of the terms on the right-hand side of the equation in order to provide an explanation of variations in mean monthly river discharges. An overview of the data and ENSO classification scheme employed in the analysis is presented in the final section.

Precipitation

The seasonal distribution of precipitation across Florida is such that most stations experience a summer (June-September) maximum (figure 3.1). This results from the combined influence of convective thunderstorms and tropical moisture systems (Jordan 1984). Thunderstorms not only develop with convectional heating of the landmass, but also due to the state's peninsular situation by which sea breezes from both the Gulf of Mexico and the Atlantic Ocean converge on the interior, providing additional uplift of air (Winsberg 1990). Differences in timing and duration of the season exist across the state. Stations located across the interior of the panhandle and north central Florida experience the highest proportion of convective rainfall during July and August, as do locations in the Gulf hammock area from Tampa north to Cedar Key (Jordan 1984). The occurrence of these storms tends to linger through September in central and southern Florida, particularly along the Gulf coast (table 3.1). In a line extending across southern Florida from Melbourne to Ft. Myers there is a double peak of summer precipitation occurring primarily in June and September/October (figure 3.1). These peaks become more pronounced further south (Jordan 1984). The intervening

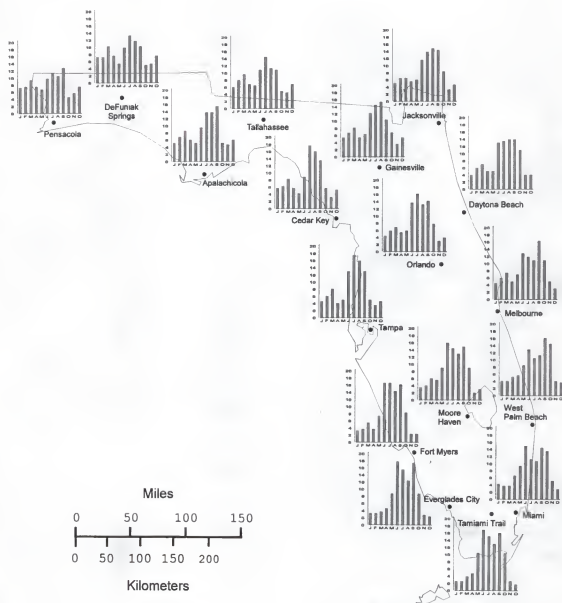


Figure 3.1 Mean monthly precipitation for selected locations in Florida. Source: Jordan 1984.

Table 3.1 Average number of days with thunderstorms

	J	F	M	A	M	J	J	A	S	O	N	D
North Florida												
Gainesville	1	4	3	3	6	13	19	20	7	6	2	1
Jacksonville	1	1	3	4	7	11	16	13	7	2	1	1
Pensacola	2	3	4	4	5	11	15	15	7	2	2	2
Tallahassee	2	2	4	4	8	13	20	17	8	2	2	2
Central Florida												
Daytona Beach	1	2	3	4	8	13	17	16	9	3	1	1
Orlando	1	2	3	3	8	15	19	17	10	3	1	1
Tampa	1	2	3	3	6	14	21	21	12	3	1	1
Vero Beach	1	2	3	4	6	13	15	17	9	5	2	1
South Florida												
Ft. Myers	1	1	2	3	7	16	23	21	14	4	1	1
Key West	1	1	2	2	4	10	13	14	11	4	1	1
Miami	1	1	2	3	7	13	15	16	12	5	1	1
W. Palm Beach	1	1	2	4	8	13	16	16	11	5	1	1

Source: Winsberg 1990.

decrease in rainfall during July and August is partially the result of the presence of the Bermuda High pressure cell in the North Atlantic, which tends to reduce the intensity, although not usually the frequency, of the convective thunderstorms (Winsberg 1990).

Nearly all tropical storms and hurricanes that develop in the North Atlantic Ocean do so during the June-November time period (Neumann et al. 1987). Greatest frequencies of occurrence tend to be from mid-August to mid-October with a peak in September (figure 3.2). Paths of these storms vary considerably. Of those that have affected Florida from 1885-1980, susceptible locations are the southern and panhandle regions (figure 3.3). Characteristics of tropical systems are also variable in that some produce relatively light winds and have abundant rainfall while others produce stronger winds and have little rainfall associated with them. Despite the variability in their characteristics, coastal stations along the panhandle experience an abundance of rainfall in September due in part to the influence of these storms. Similarly, stations in southern Florida, from Melbourne along the Atlantic coast and Ft. Myers along the Gulf coast and locations southward, have a September peak (figure 3.1). Several of the largest extreme rainfall events have been associated with tropical systems at

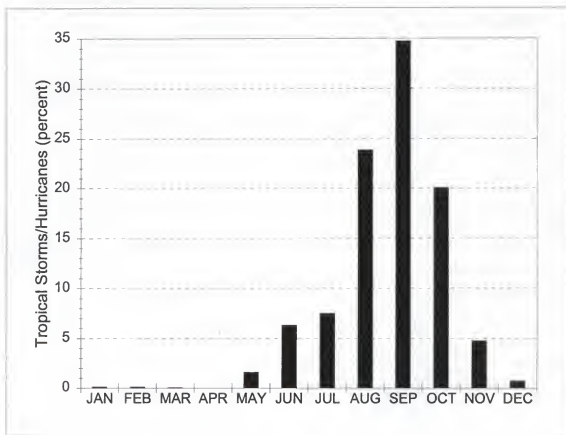


Figure 3.2 Frequency histogram of tropical storms and hurricanes in the North Atlantic Ocean, 1885-1986. Source: Neumann et al., 1987.

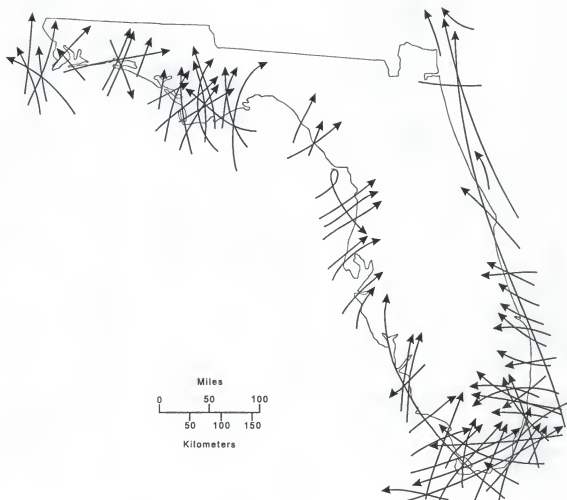


Figure 3.3 Entry points and directions of movement of tropical storms and hurricanes in Florida, 1885-1980.
Source: Jordan 1984.

locations primarily in the southern and panhandle regions of Florida (Jordan 1984).

A winter peak, which is less ubiquitous across the state, is experienced across the panhandle and portions of north central Florida (figure 3.1). Mid-latitude cyclonic activity generates much of this precipitation (Winsberg 1992) in conjunction with low pressure systems that develop over the Gulf of Mexico and, on occasion, offshore over the Atlantic (Jordan 1984; Davis et al. 1993). These systems generally weaken considerably towards the south and most of them do not affect South Florida to any great extent, as reflected in winter (December-February) precipitation expressed as a percentage of the annual total (table 3.2). Locations in North Florida tend to receive 20 percent or more of their annual totals during winter. Values gradually decrease southward to as low as 10 percent for some locations in South Florida (Jordan 1984; Winsberg 1990).

Temperature and Evaporation

Temperature and potential evaporation are directly related and both variables have seasonal summer maxima and winter minima (Winsberg 1990). The inextricable link between these variables allows temperature to indirectly represent precipitation losses to evaporation. For example,

Table 3.2 Winter precipitation as percentage of annual total

	Percentage of Annual Precipitation in Winter
North Florida	
Gainesville	20
Jacksonville	18
Pensacola	23
Tallahassee	22
Central Florida	
Daytona Beach	16
Melbourne	15
Orlando	14
Tampa	17
South Florida	
Ft. Myers	10
Key West	15
Miami	10
W. Palm Beach	13

Source: Winsberg 1990.

peaks of incoming precipitation averaged across the Santa Fe river basin are approximately 100 mm (4 in) in winter and 200 mm (8 in) in summer (figure 3.4). Outgoing runoff, also averaged across the drainage basin, peaks at about the same level (60 mm, 2.4 in) in both seasons. The reduction in runoff relative to precipitation during summer is due to greater losses of precipitation to evaporation.

Temperatures are more consistent across Florida in summer than winter as indicated by lower coefficients of variation in the average maximum (table 3.3). Little spatial variation in June-August maximum daily temperatures exists as most locations experience temperatures in excess of 32°C (90°F) (Winsberg 1990). With the exception of two narrow bands, one along the Atlantic coast and the other along the western panhandle coast, Florida averages at least 100 days/yr. with maximum temperatures of 31°C (88°F) (figure 3.5). In the southwest region the number increases to an excess of 150 days. Thus, input losses to evaporation are consistently high for extended periods of time across the study area.

Winter daily maximum temperatures are far more variable across Florida and their spatial component reflects latitudinal differences to a greater extent than during summer (figure 3.6). Across the panhandle less than 20 percent of winter maximum temperatures exceed 24°C (75°F).

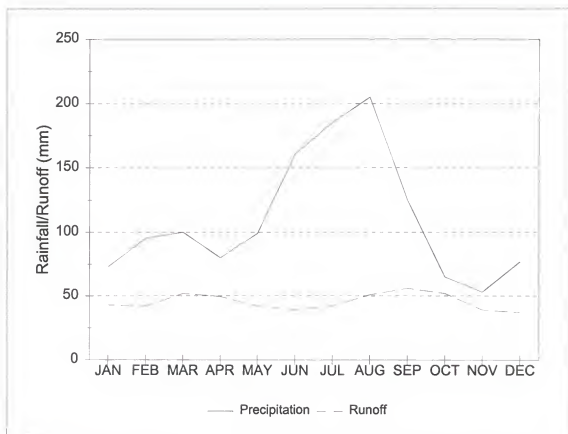


Figure 3.4 Precipitation and runoff in the Santa Fe river basin, Florida.

Table 3.3 Coefficient of variation of mean monthly maximum temperature

	J	F	M	A	M	J	J	A	S	O	N	D
North Florida												
Gainesville	6	6	4	2	2	2	1	1	1	2	4	4
Jacksonville	8	7	4	3	2	3	2	2	2	3	4	4
Pensacola	8	6	4	4	2	2	2	2	2	4	4	5
Tallahassee	8	6	4	4	2	2	2	2	2	2	4	6
Central Florida												
Daytona Beach	6	6	4	3	2	2	1	1	1	2	4	4
Melbourne	6	5	4	2	1	2	2	1	1	2	3	4
Orlando	7	5	4	2	2	2	1	1	1	2	4	4
Tampa	6	6	4	2	2	1	1	1	1	2	4	4
South Florida												
Ft. Myers	5	5	5	2	2	2	1	1	1	2	4	4
Key West	4	4	3	2	1	1	1	1	1	1	2	4
Miami	4	4	3	1	1	2	1	1	1	1	3	3
W. Palm Beach	4	4	3	1	2	2	1	1	1	2	3	3

Source: Winsberg 1990.

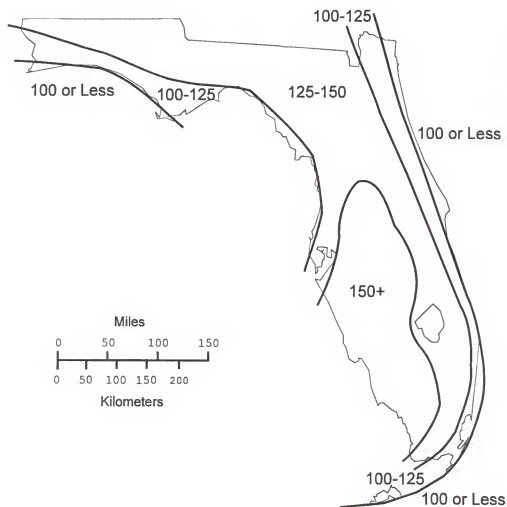


Figure 3.5 Number of days in Florida in which the mean maximum temperature is greater than 31°C (88°F). Source: Winsberg 1990.

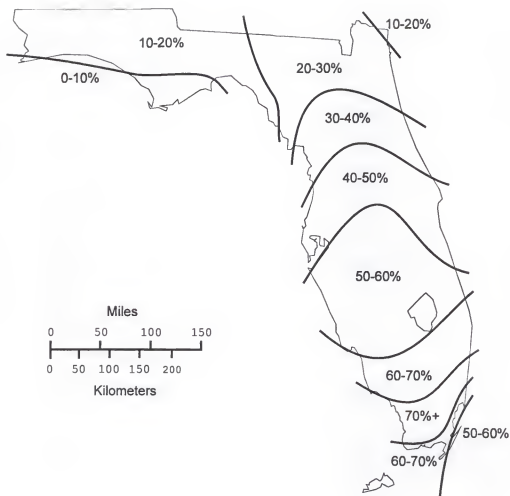


Figure 3.6. Percentage of winter days in which the daily maximum temperature exceeds 24°C (75°F). Source: Winsberg 1990.

The percentage gradually increases to 50 percent in central Florida and greater than 70 percent at inland locations of southern Florida (Winsberg 1990). A larger proportion of precipitation would then be expected to be lost to evaporation in the south than in locations farther north.

Distinction is made in winter between continental and peninsular Florida (Winsberg 1990). A steep gradient in the percentage of days in which the minimum temperature is below 4°C (40°F) exists in the north central region (figure 3.7). Locations in central Florida and further south experience these colder temperatures less than 30 percent of the time while they occur over 40 percent of the time across much of northern Florida. Because there is a large reduction in evaporation at these colder temperatures there is the tendency for higher proportions of precipitation to result in runoff in the northern sector of the study area.

Hydrologic Stores

Important stores that may operate at the monthly time scale include groundwater and possibly large lakes such as many of those found in central Florida (figure 3.8). At the annual time scale Florida receives input primarily from precipitation, most of which (75 percent) goes to evapotranspiration and the remaining portion (25 percent) as

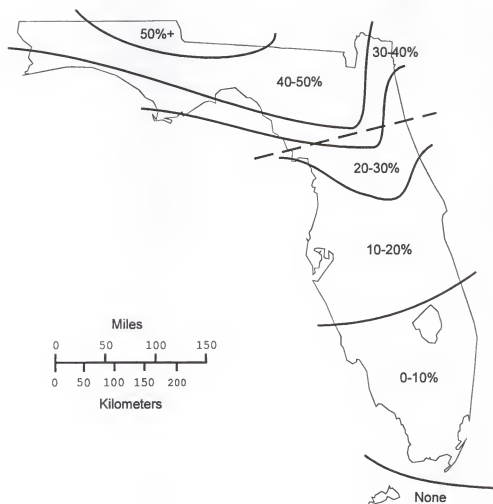


Figure 3.7 Percentage of winter days in which the daily minimum temperature is below 4°C (40°F). Source: Winsberg 1990.

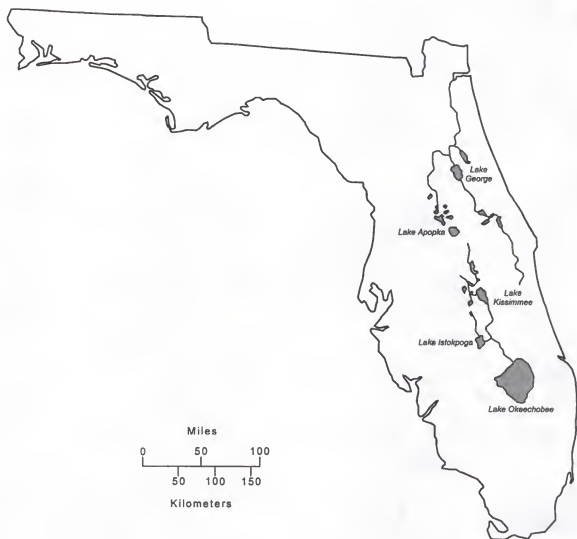


Figure 3.8 Major lakes within the Florida drainage area.
Source: Jordan 1984.

runoff (Jordan 1984). These percentages vary at the seasonal and monthly time scales.

The effects of fluctuations in groundwater recharge and discharge on monthly streamflow are difficult to assess. Streamflow responses to fluctuations in baseflow generally occur more gradually than those resulting from the direct effects of precipitation events (Jordan 1984). A study of the water balance of in a region from Tampa northward to the Gulf hammock (in west-central Florida) indicates that accumulated changes in storage closely reflect coincident positive and negative fluctuations in stages of lakes, rivers, shallow aquifers and the Floridan aquifer (Cherry et al. 1970). Response times of the stores are in-phase. The monthly distributions of cumulative storage and the surface of the Floridan aquifer also tend to increase/decrease with monthly precipitation (figure 3.9). The response of the Floridan aquifer seems to lag the precipitation by about one month, suggesting that precipitation moves fairly rapidly through the subterranean system and is a function of local hydrologic inputs. Therefore, the groundwater response may be disregarded in terms of its role within the ENSO signal. Whether this scenario applies to the entire study area is not entirely clear.

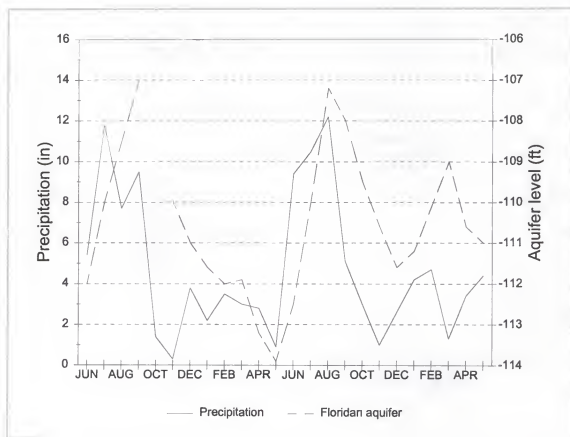


Figure 3.9 Monthly precipitation and levels of the Floridan aquifer, June 1964-May 1966. Source: Cherry et al., 1970.

Data

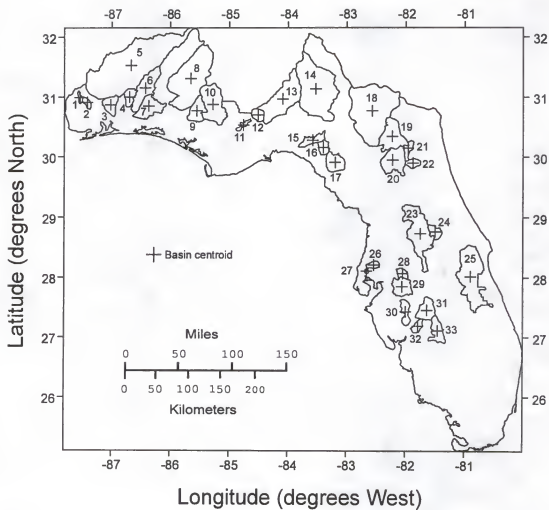
Data used in this analysis consist of mean monthly streamflows and monthly values of the Southern Oscillation Index (SOI). An a priori classification of ENSO events is required to provide the basis for subdividing the streamflow data into warm, cold and non-ENSO subsamples.

Streamflow Data

Mean monthly discharges of the selected basins are calculated from USGS daily discharge data available from EarthInfo, Inc. (1993). Florida's water year is defined from October through September; thus the 1992 water year extends from October 1991 through September 1992. Given the timings of responses in streamflow to ENSO conditions, the monthly data must be divided into a period that does not correspond to the traditional calendar year. The summer response to warm events, for example, occurs during the year of the event (year 0); however, the winter response occurs during the year following the event (year +1). Therefore, the data in this analysis extend from May of year 0 through April of year +1 in order to capture the appropriate seasonal responses to ENSO forcing. Taking the warm event of 1972 as an example, May-December will comprise 1972 flows whereas Jan-April will consist of 1973 data.

Streamflow records to be included are no shorter in length than 30 years, a figure generally supported as a minimum requisite for meaningful statistical results (Ott 1988; Griffith and Amrhein 1991). Thirty-three gaging stations are used in the analysis, ranging from 30-67 years of record (figure 3.10; appendix A). All stations have records that are 95 percent complete or greater and are not listed by the USGS as being artificially controlled or channelized. Thus, as much as possible, the records reflect natural processes. Artificial control of channels in south Florida renders these data inadequate. Similarly, there is a noticeable gap in spatial coverage within the northern portion of the study area due to the artificial structures imposed along the Chattahoochee/Apalachicola river. Multiple sampling of streamflow along any given river is also avoided. Upstream gaging stations are therefore selected in order to better represent responses to ENSO than the more integrated stations at downstream locations.

The streamflows of these stations are shown to be stationary at the $\alpha=0.05$ level. In order to model and compare flows from basins of varying size the data are standardized by basin area into units of runoff ($\text{m}^3\text{s}^{-1}\text{km}^2$). As shown in figure 3.11, the effect of basin area accounts for less than ten percent of the variability in streamflow during most months as reflected by the R^2 values. Notable



- | | | |
|-------------------------|----------------------------|----------------------|
| 1. Brushy Creek | 12. Little River | 23. Ocklawaha River |
| 2. Pine Barren Creek | 13. Ochlockonee River | 24. Wekiva River |
| 3. Big Coldwater Creek | 14. Withlacoochee River | 25. St. John's River |
| 4. Blackwater River | 15. Econfinia River | 26. Anclote River |
| 5. Escambia River | 16. Fenholloway River | 27. Brookier Creek |
| 6. Yellow River | 17. Steinhatchee River | 28. Blackwater Creek |
| 7. Shoal River | 18. Suwannee River | 29. Alafia River |
| 8. Choctawhatchee River | 19. St. Mary's River | 30. Horse Creek |
| 9. Holmes Creek | 20. Santa Fe River | 31. Charlie Creek |
| 10. Chipola River | 21. North Fork Black Creek | 32. Joshua Creek |
| 11. Telogia Creek | 22. South Fork B | 33. Fisheating Creek |

Figure 3.10 Location map of study area and drainage basins.

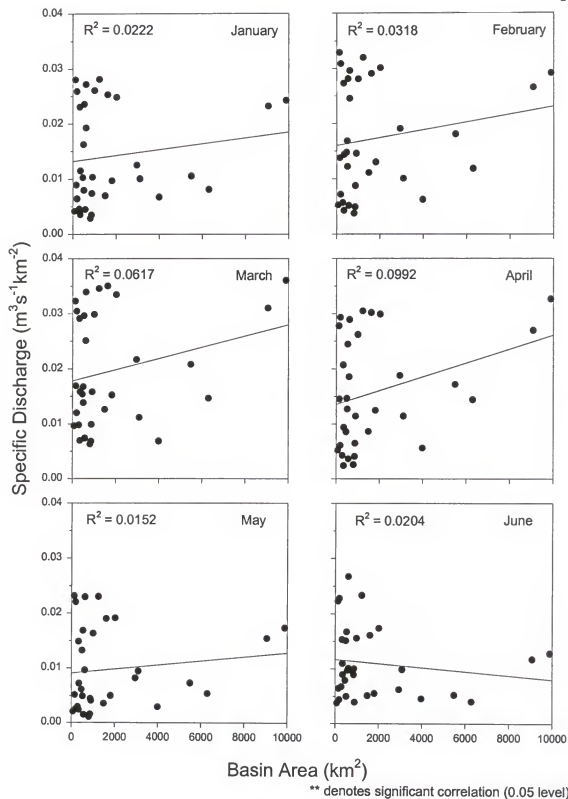


Figure 3.11 Relationship between runoff and basin area, January-December

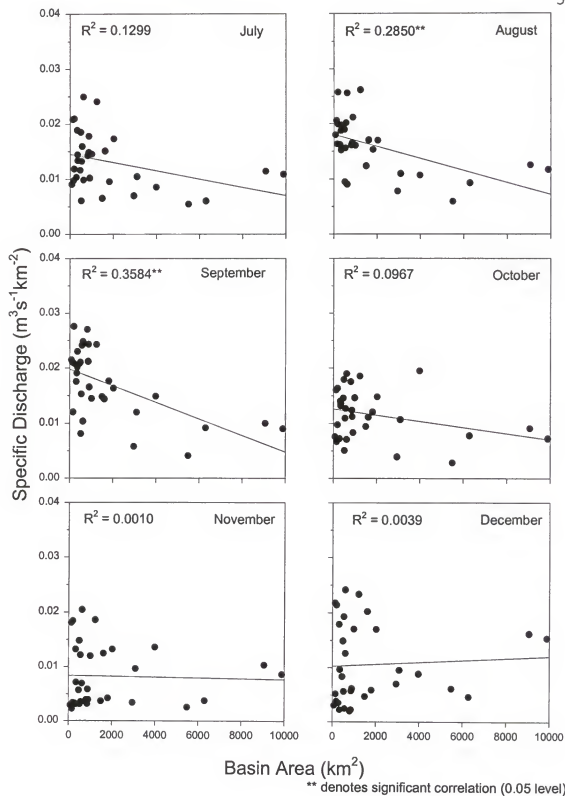


Figure 3.11 -- continued

exceptions occur during August and September during which basin area accounts for 28 and 36 percent of the variation in flows, respectively. These two are the only months to demonstrate significant correlations ($\alpha=0.05$) between basin area and runoff. A seasonal component is also evident in the association between these two variables. Although the relationship is not statistically significant, during winter-spring (December-May) runoff tends to increase with increasing basin area. By contrast, runoff tends to decrease with increasing basin area during summer-fall (June-November). These seasonal contrasts suggest that streamflow generating mechanisms during winter are regional in scope while those operating during summer produce mainly local differences in runoff.

Southern Oscillation Index

The analysis requires monthly values of the Southern Oscillation Index and these are available for all years coincident with the available discharge data (NOAA 1995). The SOI is a standardized measure of Tahiti minus Darwin atmospheric pressure at sea level. A value of zero represents the mean difference between the two stations. Positive values represent stronger high/low pressures in the eastern/western tropical Pacific and negative values

correspond to weaker high/low pressures in the eastern/western tropical Pacific.

Classification of ENSO Events

This analysis is in part guided by previous ENSO research in the southeast United States; therefore, the selection of warm years to be used is the classification developed by Rasmusson and Carpenter (1983) because monthly timings of maximum response in precipitation and streamflow to El Niño have been based upon this scheme (Ropelewski and Halpert 1986; Kahya and Dracup 1993a,c). The classification of cold years is from Ropelewski and Jones (1987) which has been used to analyze monthly responses in precipitation to La Niña events (Ropelewski and Halpert 1989). Mean monthly streamflow data are to be subdivided into warm and cold years based upon these classifications and years that are not encompassed within either category are classified as non-ENSO years (table 3.4). Kahya and Dracup (1993a) expand the list used by Ropelewski and Halpert (1986) to include 1986 as a warm year and there is some evidence to suggest that 1991 and 1992 were warm years as well (Quesada 1992). The classification of cold years devised by Ropelewski and

Table 3.4 Classification of ENSO years

Warm Years		
1902	1930	1972
1905	1939	1976
1911	1941	1982
1914	1951	1986
1918	1953	1991
1923	1957	1992
1925	1965	
1932	1969	
Cold Years		
1904	1928	1970
1909	1938	1971
1910	1950	1973
1916	1955	1975
1917	1956	1988
1924	1964	
Non-ENSO Years		
1900-1901	1929	1958-1963
1903	1931	1966-1968
1906-1908	1933-1937	1974
1912-1913	1940	1977-1981
1915	1942-1949	1983-1985
1919-1922	1952	1987
1926-1927	1954	1989-1990

Sources: Ropelewski and Halpert 1986;
 Ropelewski and Jones 1987;
 Quesada 1992.

Jones (1987) ends with the 1975 event but 1988 is classified as such in later works (Kiladis and Diaz 1989; Waylen and Caviedes 1990; Quesada 1992). Thus, there are three warm events and one cold event added as addenda to the two classification schemes employed in this study.

Concluding Remarks

A general overview of the study area in terms of a water balance approach is presented within this chapter. Specifically, temporal and spatial patterns of precipitation, temperature, evaporation and hydrologic stores are discussed in the context of variability in mean monthly streamflows. Lastly, a discussion of data to be used in the analysis and the ENSO classification is presented.

CHAPTER 4 METHODOLOGY

This chapter provides a discussion of means by which the effects of ENSO on mean monthly streamflow in Florida are to be characterized and documented. Mean monthly streamflow data are first subjected to a lag cross-correlation analysis with monthly values of the SOI to determine months in which there is a potential relationship between the two variables. The appropriate underlying probability distribution to represent the monthly streamflows at all stations is then considered. The selected distribution is applied to subpopulations of the monthly flows, determined on the basis of ENSO conditions (warm, cold and non-ENSO years). These three subgroups, each with their own parameters, are used to formulate mixture probability models at each station. Distribution parameters under all sets of conditions are spatially modeled and examined for seasonality and to assess regional differences in the influence of ENSO. The final portion of the project is concerned with the extraction of distribution parameters from the spatial models at four test gaging

stations and to estimate or predict their probabilities of monthly streamflow.

Lag Cross-Correlation Analysis

The linear association between two random variables X and Y is indicated by the population correlation coefficient, ρ_{xy} , defined as a measure of how the two variables change together (Haack 1979; Haan 1977). This coefficient is mathematically written in terms of the covariance of X and Y, σ_{xy} , and the variances of X, σ_x , and Y, σ_y , as

$$\rho_{x,y} = \frac{\sigma_{x,y}}{\sigma_x \sigma_y} \quad (4.1)$$

The estimate of the population correlation coefficient is stated in terms of sample covariance $[x,y]$ and variances of x and y as

$$r_{x,y} = \frac{s_{x,y}}{s_x s_y} \quad (4.2)$$

where $r_{x,y}$ is the sample correlation coefficient, $s_{x,y}$ is the sample covariance between X and Y and s_x and s_y are the sample standard deviations of X and Y (Haan 1977). Referred to as simple linear correlation analysis (Yevjevich 1972) it is a measure of association between two random variables,

recorded at simultaneous points in time (lag-zero correlation).

Lag k cross-correlation expands the notion of the association between two random variables to include the measure calculated when various time periods separate observations of the two variables. Specifically, it "is the correlation between one random variable at one time point and a second random variable k time points later (Haan 1977)." The model is again stated in terms of the covariation of two random variables, X and Y , and the variances of both as

$$r_{x,y}(k) = \frac{[\sum_{i=1}^{n-k} (X_i - \bar{X})(Y_{i+k} - \bar{Y})]}{(n-k) s_x s_y} \quad (4.3)$$

in which n is the total number of pairs of observations in the sequence, X_i is the i^{th} observation on X , $\bar{x}$ is the mean of the observations on X , Y_i is the i^{th} observation on Y , $\bar{y}$ is the mean of the observations on Y , and s_x and s_y are the standard deviations of X and Y , respectively.

In this analysis, the random variables are monthly values of the Southern Oscillation Index (SOI) and mean monthly values of streamflow. Benefits of such an approach are 1) no a priori classification of ENSO and non-ENSO years is required and, 2) the effort to substantiate the qualitative existence or non-existence of a relationship

between the SOI and streamflow is minimal. However, one of the underlying assumptions of the model is that both monthly SOI and mean monthly streamflows are random variables drawn from normal distributions. Because the SOI is a standardized value it meets this requirement; however, it is highly unlikely that the streamflow data are normally distributed. Furthermore, the analyses do not assess the variation within the data; they simply assess the association between monthly means. Taking this into account, the cross-correlation coefficients are to be used primarily as indicators of months which are likely to demonstrate linear associations between SOI and river discharge and the nature of the timing of that association. This portion of the study serves only as a point of departure for identifying key times of interest when analyzing the results from the proceeding sections.

Tests of statistical significance of the derived correlation coefficients are performed under the following null (H_0) and alternate (H_a) hypotheses:

H_0 : $\rho = 0$ in which there is no association between the two variables (SOI and streamflow) and

H_a : $\rho \neq 0$ in which case there is a statistically significant correlation between the two variables.

The test statistic, t , has Student's distribution with $n-2$ degrees of freedom and is denoted by the equation

$$t = r \left[\frac{(n-2)}{(1-r^2)} \right]^{0.5} \quad (4.4)$$

where r is the correlation coefficient and n is the number of paired observations between SOI and streamflow. Because the primary objective of the correlation analysis is to highlight months of interest, tests are performed at the $\alpha = 0.10$ level of significance (90% confidence level) rather than at the more limiting 0.05 significance level.

Underlying Theoretical Probability Distributions

The selection of a theoretical probability distribution to characterize mean monthly streamflows is impacted by the skewness of the empirical data (Singh and Lonquist 1974). Monthly discharges are bound on the low end by zero and are theoretically unlimited in the direction of high flows. Thus, the data are generally positively skewed (Haan 1977; Richards 1995). Because seasonality affects the data in that there are both temporal and spatial variations of flows, the theoretical distribution must also be sufficiently flexible and able to accommodate both wet and dry periods. This applies to Florida where there is evidence suggesting that the climatic anomalies associated

with ENSO affect monthly and seasonal precipitation (Douglas and Englehart 1981; Ropelewski and Halpert 1986, 1989; Richards 1995) as well as streamflow (Kahya and Dracup 1993a,c).

Frequency curves in hydrology are generally stated in terms of exceedance or nonexceedance probabilities and are constructed as probability plots. Such plotting requires that individual observations be independent of each other and representative of the underlying parent distribution (Riggs 1968). This analysis employs the Weibull plotting X position which has been shown to provide estimates that are "consistent with experience (Haan 1977)."

Characterizing the distributional form of mean monthly streamflow during warm, cold and non-ENSO years enables the summary of streamflow characteristics at a site. The method requires an a priori classification of years into each of the three categories so that the data may be subdivided accordingly (table 3.4). Distributions considered include X the gamma, normal and lognormal, each of which has theoretical underpinnings (Harms and Campbell 1967; Moreau and Pyatt 1970; Singh and Lonquist 1974; Haan 1977), and the Weibull, used in Richards' (1995) analysis of seasonal precipitation in Florida.

Gamma Distribution

The gamma probability density function (pdf) is given as:

$$\rho_x(x) = \frac{\lambda^\eta x^{\eta-1} e^{-\lambda x}}{\Gamma(\eta)} \quad (4.5)$$

for $x, \lambda, \eta > 0$, and its cumulative distribution function (CDF) as:

$$P_x(x) = \int_0^x \lambda^\eta t^{\eta-1} e^{-\lambda t} / \Gamma(\eta) dt \quad (4.6)$$

Mean, variance and coefficient of skew for the distribution are:

$$E(X) = \frac{\eta}{\lambda} \quad (4.7)$$

$$Var(X) = \frac{\eta}{\lambda^2} \quad (4.8)$$

and

$$Y = \frac{2}{\sqrt{\eta}} \quad (4.9)$$

Moment estimators of the parameters λ and η are:

$$\hat{\lambda} = \frac{\bar{X}}{S^2} \quad (4.10)$$

and

$$\gamma = \frac{\Gamma(1+\frac{3}{\alpha}) - 3\Gamma(1+\frac{2}{\alpha})\Gamma(1+\frac{1}{\alpha}) + 2\Gamma^3(1+\frac{1}{\alpha})}{[\Gamma(1+\frac{2}{\alpha}) - \Gamma^2(1+\frac{1}{\alpha})]^{\frac{3}{2}}} \quad (4.11)$$

Changes in η and λ control the shape and scale, respectively, while skewness (γ) decreases as η increases (Haan 1977).

Normal Distribution

The normal distribution pdf is expressed as:

$$\rho_x(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \quad (4.12)$$

for $-\infty < x < \infty$. Its CDF is given as:

$$\text{prob}(X \leq x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^x \exp\left[-\frac{(u-\mu)^2}{2\sigma^2}\right] du \quad (4.13)$$

where μ and σ are the parameters mean and standard deviation of the distribution (Haan 1977). The normal distribution is bell-shaped and symmetrical about μ ; thus, the coefficient of skew is zero and the expected values of mean and variance are described by μ and σ^2 , respectively. Moment estimators of the parameters μ and σ^2 are:

$$\hat{\mu} = \bar{X} = \frac{1}{n} \sum_{i=1}^n x_i \quad (4.14)$$

and

$$\hat{\sigma}^2 = S^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{X})^2 \quad (4.15)$$

Lognormal Distribution

The lognormal pdf is given as:

$$\rho_x(x) = \frac{1}{x\sigma_y\sqrt{2\pi}} \exp\left[-\frac{(\ln(x) - \mu_y)^2}{2\sigma_y^2}\right] \quad (4.16)$$

for $x > 0$, and its CDF results from the standard normal CDF as:

$$\text{prob}(Y \leq y) = \int_{-\infty}^y \frac{1}{\sigma_y\sqrt{2\pi}} \exp\left[-\frac{(u - \mu_y)^2}{2\sigma_y^2}\right] du \quad (4.17)$$

where $y = \ln(x)$ and μ_y and σ_y are the parameters mean and standard deviation of the distribution (Haan 1977). Mean, variance and coefficient of skew of the distribution are given by Haan (1977) and Evans, et al. (1993) as:

$$E(X) = \exp\left(\mu_y + \frac{\sigma_y^2}{2}\right) \quad (4.18)$$

$$\text{Var}(X) = \mu_x^2 [\exp(\sigma_y^2) - 1] \quad (4.19)$$

and

$$\gamma = [\exp(\sigma_y^2) + 2] [\exp(\sigma_y^2) - 1]^{1/2} \quad (4.20)$$

Maximum likelihood estimates of mean (μ) and variance (σ^2) are derived from the normal distribution by transformation as:

$$\hat{\mu} = \frac{1}{n} \sum_{i=1}^n \ln x_i \quad (4.21)$$

and

$$\hat{\sigma}^2 = \frac{1}{n-1} \sum_{i=1}^n [\ln(x_i - \hat{\mu})]^2 \quad (4.22)$$

Weibull Distribution

The Weibull pdf is given as:

$$\rho_x(x) = \alpha x^{\alpha-1} \beta^{-\alpha} \exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right] \quad (4.23)$$

for $x \geq 0$; $\alpha, \beta > 0$. The CDF is given as:

$$P_x(x) = 1 - \exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right] \quad (4.24)$$

Mean, variance and coefficient of skew of the distribution are:

$$E(X) = \beta \Gamma\left(1 + \frac{1}{\alpha}\right) \quad (4.25)$$

$$\text{Var}(X) = \beta^2 \left[\Gamma\left(1 + \frac{2}{\alpha}\right) - \Gamma^2\left(1 + \frac{1}{\alpha}\right) \right] \quad (4.26)$$

and

$$\gamma = \frac{\Gamma\left(1 + \frac{3}{\alpha}\right) - 3\Gamma\left(1 + \frac{2}{\alpha}\right)\Gamma\left(1 + \frac{1}{\alpha}\right) + 2\Gamma^3\left(1 + \frac{1}{\alpha}\right)}{\left[\Gamma\left(1 + \frac{2}{\alpha}\right) - \Gamma^2\left(1 + \frac{1}{\alpha}\right) \right]^{\frac{3}{2}}} \quad (4.27)$$

The shape and scale parameters, α and β , respectively, are estimated via the method of moments by substituting the sample mean and variance in the above equations and solving for α and β (Haan 1977).

Mixture Model

A hydrological random variable, x , that results from one of several possible processes has a probability distribution, F_x , which is the sum of the processes, each weighted according to its frequency of occurrence, g_k . Thus, for the subdivided streamflow data, the mixed distribution is

$$F_x(X \leq x) = \sum_{k=1}^m g_k F_k(X \leq x) \quad (4.28)$$

where F_k is the distribution of each subsample of climatic conditions and where

$$\sum_{k=1}^m g_k = 1.0 \quad (4.29)$$

and k represents warm, cold and non-ENSO sub-samples. The selected parent probability distribution will be characterized in this mixed form in order to assess whether the fitted function based upon ENSO is an improvement upon the non-subdivided fit.

Goodness-of-Fit

Testing of empirical data to theoretical form is achieved through the use of the Kolmogorov-Smirnov (K-S) goodness-of-fit test, which is set-up as follows:

$$H_0: F(x) = G(x)$$

$$H_a: F(x) \neq G(x)$$

where $F(x)$ is the theoretical parent probability distribution and $G(x)$ is the empirical distribution. Failing to reject the null hypothesis when it is in reality false is known as a Type II statistical error. In order to reduce the probability of committing this error a significance (α) level of 0.20 is used throughout the analysis.

Assumptions regarding the K-S statistic are: 1) the population frequency distribution must be continuous, and 2) observations must be independent (Griffith and Amrhein 1991). Both assumptions are satisfied using mean monthly values of streamflow. The statistic is given as:

$$K-S = \max |F_x - G_x| \quad (4.30)$$

where max is the maximum difference between the empirical and theoretical values. The test will be applied to each of the four distributions (gamma, normal, lognormal and Weibull) as well as to the mixed distribution.

Spatial Analysis

The spatial variation in distribution parameters under various climatic conditions is modeled via trend surfaces. Specifically, first, second and third order surfaces are tested for their abilities to satisfactorily model ($\alpha=0.05$ level) the parameters of the selected distribution under

warm, cold and non-ENSO climatic states for every month. Goodness of fit is assessed not only by testing the statistical significance of each surface, but also by examining the percentage of variation in each parameter that is explained by the fitted surfaces. Analysis of residuals is performed to assess how well each surface conforms to the underlying model assumptions of trend surfaces. Confidence surfaces are constructed ($\alpha=0.05$) about each fitted surface yielding upper and lower confidence values for each parameter. The objective of these trend surface analyses is to fully characterize the spatial variability of streamflow response to ENSO.

The final section entails testing the efficacy of the spatial models by estimating the requisite parameters at four test stations from the appropriate trend surfaces. These estimates are substituted into the selected probability distribution and predicted probability distributions are generated for all months.

Trend Surfaces

Trend surfaces are expressed mathematically in a general form as:

$$Z_i = f(x_i, y_i) + u_i \quad (4.31)$$

where Z_i is the predicted value of the trend surface at the i th data point, x_i is the longitudinal coordinate of the i th

point, y_i is the latitudinal coordinate of the i th point and u_i is the residual at the i th data point (Krumbein and Graybill 1965; Unwin 1975). In the simplest of cases a planar surface is fitted to the observed parameters of each sample gaging station and is referred to as a 1st order or linear surface. Basin centroids are used as inputs for latitude and longitude and the equation of the surface is expressed as:

$$z_i = a_0 + a_1 x_i + a_2 y_i + u_i \quad (4.32)$$

where a_0 is the value of the parameter at the map origin, a_1 represents the rate of change in the value along the longitudinal axis, a_2 represents the rate of change in the value along the latitudinal axis (Williams 1986).

First order surfaces have the merit of simplicity but they may not adequately account for the variation in the parameter of interest. Second order (quadratic) surfaces describe trends as domes or troughs across the study area and are expressed as:

$$z_i = b_0 + b_1 x_i + b_2 y_i + b_3 x_i^2 + b_4 x_i y_i + b_5 y_i^2 \quad (4.33)$$

where the b 's are coefficients representing rates of change in each of the terms. Third order (cubic) surfaces, involving the calculation of ten coefficients, are given as (Williams 1986; Marsal 1987):

$$\begin{aligned}
 z_i = & C_0 + C_1 X_i + C_2 Y_i + C_3 X_i^2 + C_4 X_i Y_i + C_5 Y_i^2 + \dots \\
 & \dots C_6 X_i^3 + C_7 X_i^2 Y_i + C_8 X_i Y_i^2 + C_9 Y_i^3
 \end{aligned}
 \tag{4.34}$$

Evaluation of Fit

Goodness of fit of each of the trend surfaces to the parameters is assessed with Fisher's F-ratio ($\alpha=0.05$) under the null hypothesis that the total trend is equal to zero. Two sources of variation are present in the trend surface model--those of the trend (regression) and residual (error) components. Total variation in the sum of squares (TSS) is the sum of the regression (RSS) and error (ESS) sums of squares. That is, $TSS = RSS + ESS$ and the F statistic is calculated as:

$$F = \frac{RSS/df_1}{ESS/df_2} \tag{4.35}$$

where RSS is the variation in the parameter explained by the surface, ESS is variation left unexplained by the surface and df_1 and df_2 are the degrees of freedom associated with the trend surface and residuals, respectively.

The coefficient of determination, R^2 , is expressed as RSS/TSS and is frequently used to identify the proportion of variation in the parameter of interest that is explained by the regression model (Griffith and Amrhein 1991). Although the number of calibration stations (samples) used to model the parameters is either 32 (for cold events) or 33 (for

warm and non-ENSO subsamples), the fact that 2nd order trend surfaces require estimation of six coefficients (ten for 3rd order surfaces) reduces the residual degrees of freedom to either 26 or 27 (22 or 23 in the 3rd order case). Thus, a more representative measure of the variation accounted for by the trend surface is given by the adjusted R^2 , defined as:

$$R_{adj}^2 = 1 - (1 - R^2) \left(\frac{n-1}{n-k} \right) \quad (4.36)$$

where R^2 is previously defined, n is the sample size or number of stations employed in the generation of the surface, and k is the number of coefficients to be estimated (2 in the linear case, 6 for a 2nd order surface and 10 for the 3rd order).

A modified form of the F-ratio is used to assess the significance in the fit of a surface of order $n+1$ beyond that of a surface of order n . The equation is given as:

$$F = \frac{(R_1^2 - R_2^2) / df_3}{(1 - R_2^2) / df_4} \quad (4.37)$$

where df_3 is the degrees of freedom associated with the added terms (3 for a 2nd order over a 1st order, 4 for a 3rd order over a 2nd order), df_4 is the degrees of freedom associated with the residuals, R_1^2 and R_2^2 are the proportions of variance explained by the lower and higher order surfaces, respectively (Unwin 1975).

Analysis of Residuals

Underlying assumptions of the trend surface model are tested for potential violations by examining the residuals or error terms of each trend surface. Independence is tested at the $\alpha=0.05$ level in which the residuals are regressed against values of predicted runoff. The null hypothesis is that no significant trend exists in the relationship. Normality of the error terms is tested by employing the Kolmogorov-Smirnov goodness of fit test ($\alpha=0.20$). Finally, homoscedasticity (constant variance within the residuals) is visually checked.

Confidence Surfaces

Once an appropriate order of trend surface is selected, confidence surfaces ($\alpha=0.05$) about each of the fitted surfaces are to be generated. This provides an interval for all points within the bounds of the study area rather than the more limiting single surface. The general form of the equation for a confidence surface is given as:

$$Z(X, Y)_i \pm (kF_{\alpha} Q^2 s^2)^{\frac{1}{2}} \quad (4.38)$$

where $Z(X, Y)_i$ is the predicted parameter for each grid point (longitude X, latitude Y), F_{α} is the critical value of F for (k,m) degrees of freedom. For a linear surface fitted to 33 map points, $k=2$ and $m=30$. The value Q^2 is analogous to the standard error of estimate of the surface coefficients and

is computed via matrix algebra based upon the X,Y coordinates. The term s^2 is the sample variance of the deviations from the fitted surface and is calculated from:

$$s^2 = \frac{\sum e_i^2}{n-k-1} \quad (4.39)$$

where e_i is the residual at the i th point and n is the number of grid points (Krumbein 1963).

Prediction

In order to test the efficacy of prediction, the parameters from four test stations are estimated based upon each of the trend surface models. Expected parameter values are calculated for warm, cold and non-ENSO conditions, employing the basin centroid of each test station. These estimates are substituted into the mixed probability model and predicted distributions of flows are generated. Predicted functions are assessed via 1) the standard Kolmogorov-Smirnov goodness of fit test, outlined earlier in this chapter, 2) estimation of parameters based on the 95 percent confidence surfaces and 3) the calculation of confidence intervals ($\alpha=0.05$) about the predicted cumulative distribution function.

Predicted cumulative distribution functions are tested ($\alpha=0.20$) for fit to the empirical data in the same manner as

that outlined earlier in this chapter. In addition to the theoretical functions that are based upon the estimated parameters from the fitted surfaces, additional functions are calculated using parameter estimates from the upper and lower confidence surfaces. In order to minimize the number of generated functions, additional functions are calculated based upon only the highest and lowest parameters of each climatic state (warm, cold, non-ENSO). The KS goodness of fit test is also used to assess these fits.

Finally, confidence intervals ($\alpha=0.05$) are constructed about the predicted cumulative distribution functions from the fitted trend surfaces. The equations are based upon recurrence interval and sample size as:

$$y = -\log_e[-\log_e(1 - \frac{1}{T})] \quad (4.40)$$

and

$$2\sigma y = 2\sqrt{\frac{T}{n}} \quad (4.41)$$

where T is the recurrence interval of interest, y is a function of the recurrence interval T and n is the number of years of record (Dalrymple 1960).

Concluding Remarks

Detailed methods by which mean monthly streamflows are to be temporally and spatially characterized have been

presented in this chapter. A lag cross-correlation analysis between the monthly flows and monthly values of the SOI is performed so that potential relationships between discharge and ENSO may be identified. The candidate parent probability distribution of the monthly streamflows is determined and applied to their subpopulations based upon warm, cold and non-ENSO conditions. The parameters of these subgroups are used to generate mixed probability distributions at each gaging station. Distribution parameters are also spatially modeled in order to assess timings and regional differences of the effects of ENSO upon streamflow across the study area. Finally, distribution parameters of four test gaging stations, previously unused in the analysis, are estimated from the spatial models and substituted into the selected mixed probability distribution so that predictions or probabilities of all flows may be rendered.

CHAPTER 5 AT-A-STATION RESULTS

This chapter provides a general overview of the results obtained from at-a-station analyses and their spatial variation. Analyses comprise 1) cross correlations, 2) investigation of candidate probability distributions without regard to ENSO conditions, 3) application of the selected distribution to ENSO and non-ENSO sub-populations, and 4) application of a mixed distribution incorporating characteristics derived from each set of ENSO conditions.

Cross-Correlation Analysis

Simultaneous and lag cross-correlations of monthly streamflow and SOI are calculated and tested for significance for each of the 34 sample stations ($\alpha=0.10$). Lagged SOI values extending 36 months prior to and following the observed streamflows are summarized in figure 5.1. In this figure, zero on the SOI axis corresponds to simultaneous correlations between SOI and observed streamflow for specified months (January-December) indicated on the vertical axis. Simultaneous positive correlations

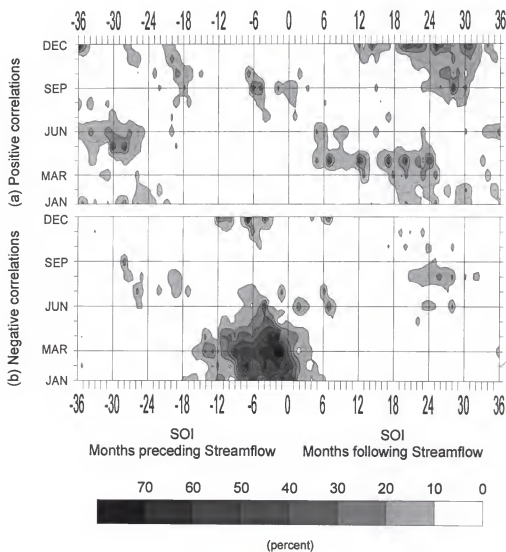


Figure 5.1 Lag cross-correlations between monthly values of streamflow and SOI, $\alpha=0.05$

(figure 5.1a) between the two variables occur at 10-20 percent of the stations during the late summer months of August-October. By contrast, negative correlations (figure 5.1b) occur primarily during the winter months of January-March (50-60 percent of stations), and extend into May. Streamflow is therefore likely to be above average in summer during cold, high SOI events and above average in winter during warm, low SOI events. These simultaneous correlations suggest that streamflow in the state is associated with ENSO during both winter and summer seasons.

The correlation seems to extend over a longer winter period than summer; that is, the winter association is a more persistent phenomenon. In figure 5.1 negative values to the left of zero on the SOI axis correspond to correlations with the SOI in 1,2,...,36 months prior to the observed streamflow of a specified month. Negative correlations (figure 5.1b) exist at 10-20 percent of the stations as much as 12 months prior to the observed streamflow. As many as 50 percent of the stations are negatively associated with SOI up to 8 months preceding the observed flows. By comparison, in summer only 10-20 percent of the stations are positively correlated with SOI prior to the observed flow and the correlation persists only for a few months.

Values to the right of zero on the SOI axis (figure 5.1) correspond to correlations between SOI for 1,2,...,36 months following the observed streamflow of a specified month. A high percentage (50-60) of stations exhibit positive correlations with SOI between 18-30 months following the observed streamflows (figure 5.1a). Similarly there is a cluster of negative associations during the summer months from about 20-28 months following the observed flows (figure 5.1b). Because of the tendency for warm and cold events to follow each other on a more or less 24-month cycle (Ropelewski and Halpert 1986), these clusters of response are interpreted as echoes of those responses which occur closer to simultaneous periods. That is, since streamflow is negatively correlated with SOI during winter (figure 5.1b), and is therefore likely to be above average during warm (low SOI) events, the positive correlations indicated at SOI 18-30 months after the observed flows (figure 5.1a) reflects the tendency for cold events to follow warm events. Similarly, negative associations during summer at SOI 20-28 months after the observed streamflows (figure 5.1b) likely are echoing the positive correlations that exist closer to simultaneous periods (figure 5.1a).

Theoretical Probability Distributions

Four theoretical probability distributions--lognormal, Weibull, gamma, and normal--are tested ($\alpha=0.20$ level to reduce probability of Type II error) against the observed mean monthly streamflows at each station for goodness-of-fit. Figure 5.2 shows the relative overall efficacy of each candidate distribution in modeling the unsubdivided streamflows. The lognormal model provides an adequate fit at the largest number of stations (nearly 70 percent). The Weibull and gamma distributions perform roughly equally, providing good fits for less than 50 percent of the samples and the normal distribution is clearly inadequate. When their relative performances are viewed on a monthly basis (figure 5.3) the lognormal provides the best overall fit, bettered only by the Weibull and gamma in February and the gamma in August. The percentage of stations at which the null hypothesis of lognormality provides an adequate fit decreases during both the May-June and October transition periods, but during no month does this percentage fall below fifty. The lognormal model provides a significant fit to over 60 percent of the stations during ten of the months. In contrast, both the Weibull and gamma distributions are adequate less than 50 percent of the time during May-June and September-December.

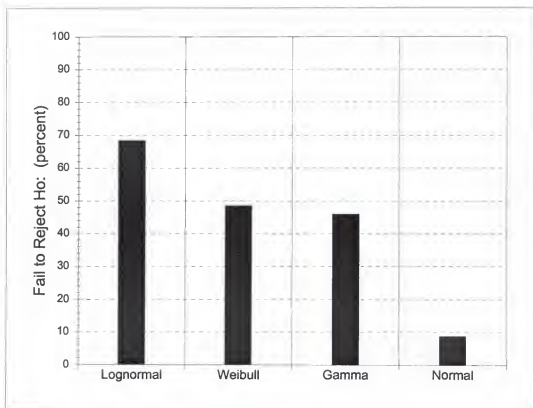


Figure 5.2 Theoretical probability distributions: All months, unsubdivided by ENSO classification

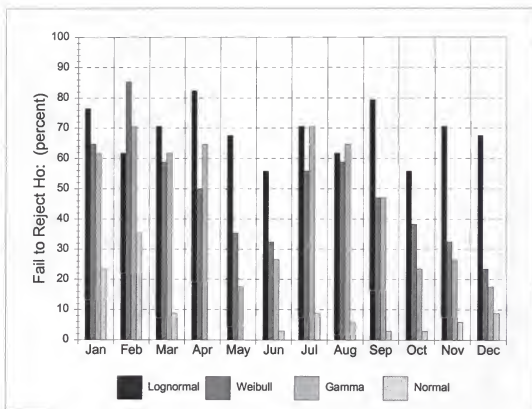


Figure 5.3 Monthly theoretical probability distributions, unsubdivided by ENSO classification

Examples of the four theoretical distributions and their fits to the empirical data are shown in probability plots for the months of February and September in figures 5.4 and 5.5. February generally represents the beginning of the winter high flow season across north Florida while September is typically a month of high flow across the entire study area. The six stations are represented in geographic order from the western panhandle to the southern portion of the study area (figure 5.6) and are used as examples throughout the remainder of this section. Streamflows are represented on the y-axis in units of specific discharge ($\text{m}^3\text{s}^{-1}\text{km}^{-2}$) in order to facilitate comparisons between the basins. The scale is the common logarithm and the data will plot as straight lines if they are lognormally distributed. Cumulative probabilities are shown as percentages along the x-axis. If the data are shown to be not significantly different from lognormal then the mean of the observations will plot at the 50 percent cumulative probability.

Examining the six stations during February (figure 5.4) it is apparent that the mean streamflow is greatest in the panhandle and decreases southward. This is expected given the dominant physical processes operating at this time. Cold fronts and their attendant precipitation more frequently cross the panhandle and north-central Florida

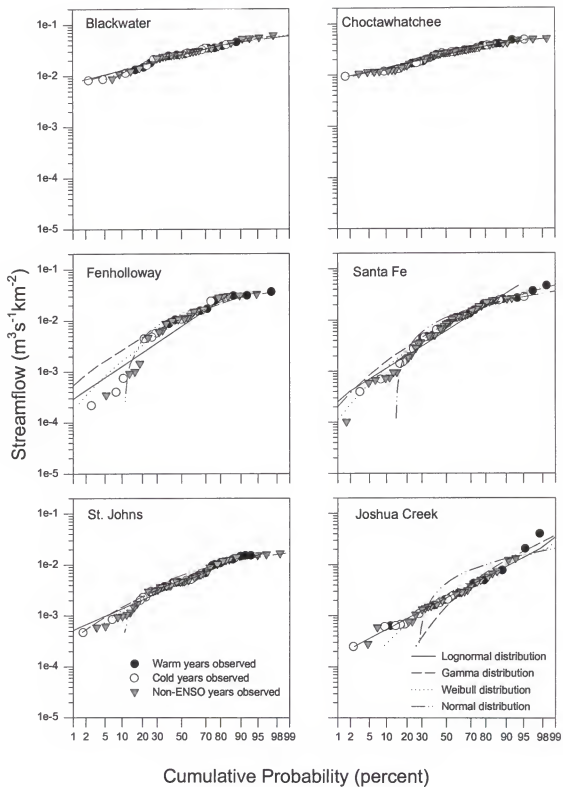


Figure 5.4 Fitted theoretical probability distributions to observed streamflows, February

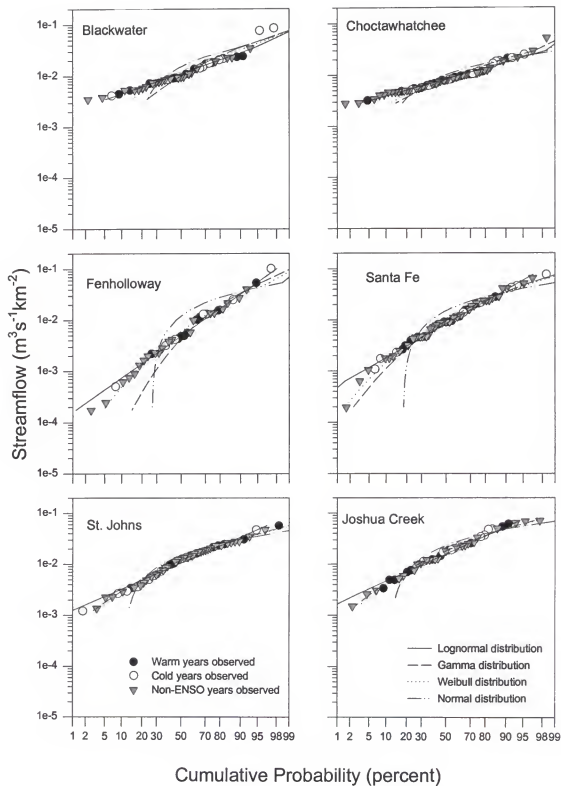


Figure 5.5 Fitted theoretical probability distributions to observed streamflows, September

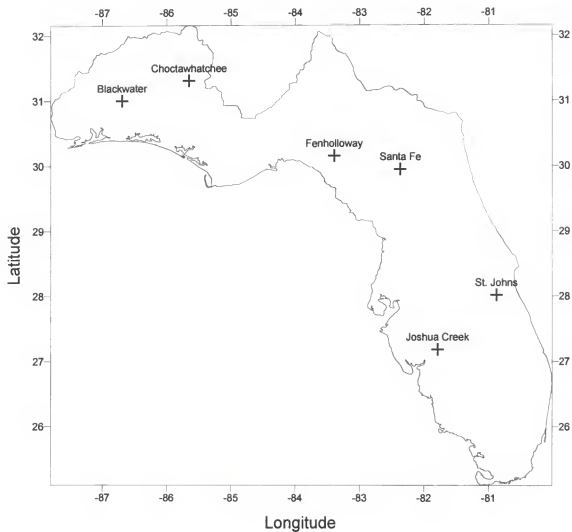


Figure 5.6 Location of gaging stations used as representative examples

than they do the southern region. There are occasions when they do penetrate into the south and this is reflected in the historic records of the St. Johns River and Joshua Creek. However, flows tend to be higher and more consistent across the panhandle than in the southern region during February.

Only the Weibull distribution cannot be considered significantly different from the observed streamflows at all six stations during February. The gamma is appropriate for four of the six (not for the Fenholloway or Joshua Creek), the lognormal for only one (Joshua Creek) and the normal distribution is not adequate at all. Although the lognormal model does not appear to be satisfactory for the high flow month of February, it will be shown in subsequent discussions that by considering ENSO conditions a lognormal mixture may be generated that is appropriate for modeling the historic records.

There is the tendency for warm years to plot at relatively high discharges, particularly across the peninsula. By contrast this same region tends to experience lower discharges during cold years. Such differences suggest that there are potentially significant differences in mean flows between warm and cold events. This response is expected given the literature on ENSO and its effects upon the precipitation generating mechanisms and the

preceding lag cross correlations. During warm years the subtropical jet stream is enhanced and it tends to advect moisture across the peninsula while during cold years this jet weakens and the polar jet stream tends to be displaced to the north and west, resulting in lower discharges.

The literature suggests that the entire state of Florida lies within a larger region of homogeneous response to ENSO. Therefore the response that is observed between warm and cold events across the peninsula would also be expected across the panhandle. However, the records for the two example panhandle stations (Blackwater and Choctawhatchee) indicate that warm years tend to fall within the central portion of the distribution at moderate flows. Cold years tend to plot along a wider range of observed flows than do the warm years, suggesting the potential for wider variations in flow rather than differences in means.

During September the highest discharges occur across south-central Florida at St. Johns river and Joshua Creek (figure 5.5). This agrees with the physical processes occurring during this period, primarily the propensity of convective thunderstorm activity across the peninsula. Tropical storm and hurricane activity also contributes to the runoff experienced during the summer season. The literature states that the frequency of these storms throughout the North Atlantic Ocean is below average during

warm years and above average during cold years. Such findings suggest that if ENSO affects runoff during this season, there is a greater likelihood that the response would be seen during cold years when the overall frequency of these storms increases. The Blackwater river in the panhandle shows that flows in warm years lie along the lower and middle portions of the distribution. Streamflow during cold years is seen throughout the entire distribution with the two largest observations occurring during these events. Although not as dramatic, cold year events tend to lie at higher nonexceedances throughout the remaining stations as well, with the exception of the St. Johns. This again suggests a potential difference in mean flows between warm and cold events.

Reviewing the efficacy of the hypothesized probability distributions during September, the lognormal cannot be considered significantly different from the observed flows for any of these stations. The gamma and Weibull models are appropriate only across the peninsula and the normal is clearly inadequate.

Subdividing the data into warm, cold and non-ENSO classes reduces effective sample sizes accordingly. Of these three sub-populations it is the non-ENSO category that has the largest sample sizes at all stations. Figure 5.7 indicates that the lognormal model is again the most

appropriate overall. Sample sizes of warm and cold years are small, ranging from 3 to 15. As such, even the hypothesis of normality fails to be rejected in over 75 percent of all cases (figure 5.8). The remaining three distributions provide significant fits over 90 percent of the time, with, once again, the lognormal performing marginally better. The monthly distribution of subdivided years (table 5.1) indicates that all models perform more poorly during transition periods, similar to the unsubdivided data. Examining non-ENSO years, the lognormal model provides a significant fit over 70 percent of the time during all months, is significant at least 90 percent of the time during 5 months, and has a better overall fit than either the Weibull or gamma distribution. For the two ENSO sub-populations the lognormal performs marginally better than the other distributions.

Overall, the lognormal distribution performs better under all conditions and months, both unsubdivided and subdivided, proving adequate in 87 percent of the samples (figure 5.9). The Weibull and gamma distributions are nearly identical in their performances at about 75 percent and the normal distribution is poor, with the null hypothesis being rejected in over 50 percent of the samples.

The probability distributions of monthly flows, subdivided into warm, cold and non-ENSO years are shown for

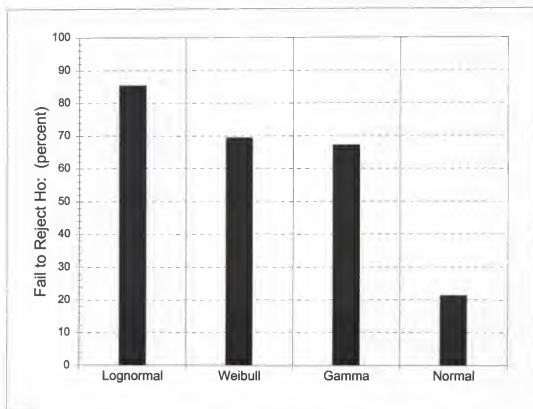


Figure 5.7 Theoretical probability distributions: All months, non-ENSO years

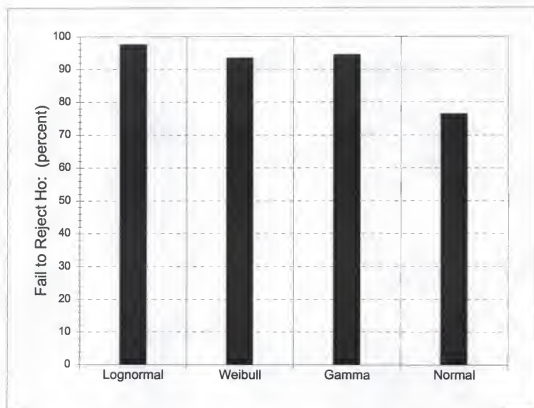


Figure 5.8 Theoretical probability distributions: All months, ENSO (warm and cold) years

Table 5.1 Percent of stations which fail to reject H_0 .

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Warm years												
LOG	100	100	97.1	94.1	97.1	97.1	94.1	97.1	100	97.1	97.1	97.1
WEI	100	100	100	88.2	91.2	94.1	97.1	91.2	94.1	94.1	79.4	88.2
GAM	100	100	97.1	100	85.3	94.1	94.1	91.2	91.2	94.1	88.2	97.1
NOR	82.4	91.2	94.1	79.4	47.1	70.6	88.2	76.5	76.5	82.4	52.9	64.7
Cold years												
LOG	100	100	97	93.9	100	100	97	93.9	100	97	97	100
WEI	97	100	90.9	87.9	87.9	90.9	90.9	90.9	100	97	93.9	100
GAM	100	100	93.9	90.9	93.9	87.9	97	100	100	90.9	97	84.8
NOR	87.9	87.9	78.8	81.8	75.8	63.6	90.9	78.8	84.8	69.7	72.7	57.6
Non-ENSO years												
LOG	94.1	82.4	91.2	94.1	79.4	85.3	94.1	82.4	94.1	76.5	76.5	73.5
WEI	82.4	97.1	79.4	73.5	67.6	52.9	79.4	79.4	61.8	52.9	47.1	58.8
GAM	85.3	85.3	85.3	82.4	55.9	47.1	82.4	82.4	64.7	47.1	41.2	47.1
NOR	35.3	55.9	14.7	23.5	20.6	5.9	20.6	23.5	14.7	8.8	14.7	17.6

n=33 gaging stations

LOG = Lognormal distribution

WEI = Weibull distribution

GAM = Gamma distribution

NOR = Normal distribution

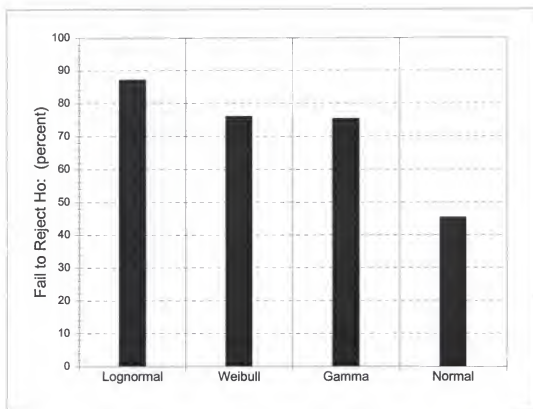


Figure 5.9 Theoretical probability distributions: All conditions and months

comparative purposes in figures 5.10 and 5.11 for February and September, respectively. During February the greatest contrasts between warm and cold events are seen throughout the peninsula (figure 5.10). Warm years consistently plot at the highest values of runoff while cold years tend to plot at the lower flows, confirming the hypothesized advection of moisture into the region by the subtropical jet stream (Douglas and Englehart 1981; Ropelewski and Halpert 1986). During cold years, however, the mechanisms that produce high runoff tend to weaken considerably (Ropelewski and Halpert 1989; Henderson and Robinson 1994). This is particularly evident across the peninsula where the observed flows during cold years are among the lowest during the periods of record. The panhandle, however, reflects little difference in terms of mean flow between warm and cold events. This identification of the western panhandle as a region of potentially separate response has not been put forth previously.

In September there is evidence to suggest that ENSO may have a greater effect across the northern portion of the study area (figure 5.11). Larger means may be observed during cold years across the panhandle (Blackwater and Choctawhatchee) while in north-central Florida the means appear to be similar between ENSO conditions. This may be related to the difference in frequencies of tropical storms.

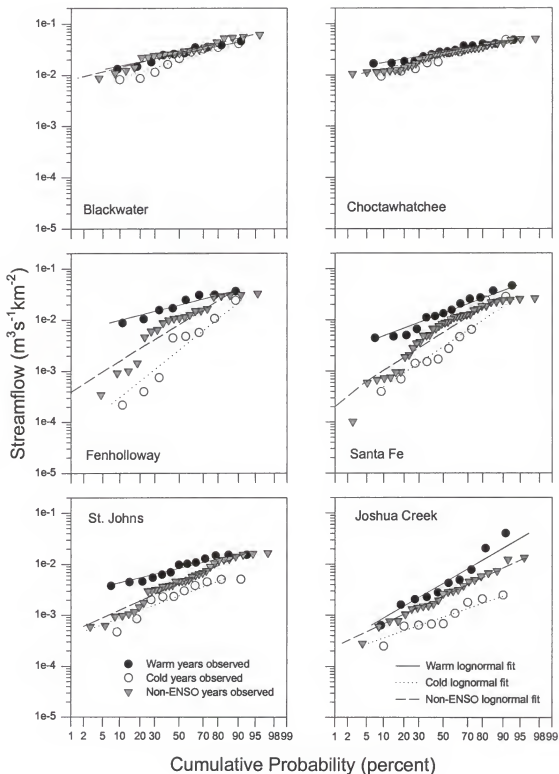


Figure 5.10 Fitted lognormal probability distributions to observed subpopulations of streamflows, February

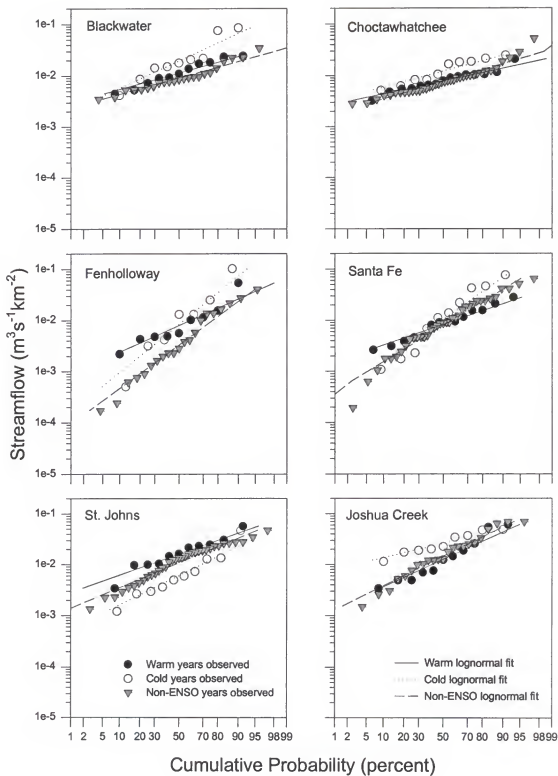


Figure 5.11 Fitted lognormal probability distributions to observed subpopulations of streamflows, September

They tend to be higher in the panhandle than north-central Florida. The signal is not as clear in the south where streamflow during warm years is greater than that during cold years for the St. Johns, but is reversed for Joshua Creek.

Since the lognormal model provides the most adequate fit to the monthly streamflows, and there is considerable evidence for an effect of ENSO on monthly distributions, the mixed lognormal distribution is calculated for each calibration station employing the parameters of mean and standard deviation for warm, cold and non-ENSO subsamples. Its application improves fit over the undifferentiated lognormal in all months except October and November (figure 5.12). During the winter high flow season, January-April, the distribution is appropriate to no fewer than 80 percent of the stations, with a maximum of 94 percent during February. Improvement over the undifferentiated model is the greatest during February (32 percent) and least during April (3 percent). The mixture model also improves the percentage fit during the summer high flow season. Greatest improvements occur in September (from 80 to over 90 percent). The most improvements occur during the high flow seasons, when the greatest ENSO influence is postulated. In particular, the mixed lognormal provides the highest percentages of fit during February and August, two months

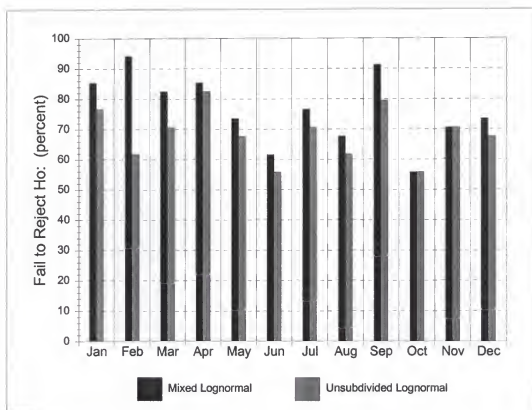


Figure 5.12 Comparison between ENSO mixed lognormal and unsubdivided lognormal probability distributions

during which the unsubdivided model failed to be the most applicable (figure 5.3). This reinforces the notion that the model is the most appropriate of those tested for all monthly streamflows across the study area.

Unsubdivided and subdivided (mixture) lognormal distributions are shown for the six example stations across Florida in figures 5.13 and 5.14 during February and September, respectively. In February the mixture model provides a significant fit to the historic records at all six stations whereas the unsubdivided model is significant only at Joshua Creek. Although the undifferentiated model is adequate for these stations during September, an improvement in fit is still seen by employing the mixture model.

The mixed lognormal model is able to accomodate a variety of shapes more complex than the unsubdivided model. For example, the Fenholloway and Santa Fe rivers (figure 5.13) take on a convex form whereas Joshua Creek (figure 5.13) and Blackwater river (figure 5.14) have a concave form. The mixture model provides sufficient flexibility, particularly within the tails of the distributions, to provide adequate fits to the historic streamflows. Combinations of concave and convex forms give rise to distributions with a characteristic "S" shape as seen in the Choctawhatchee and St. Johns rivers (figure 5.13). Again,

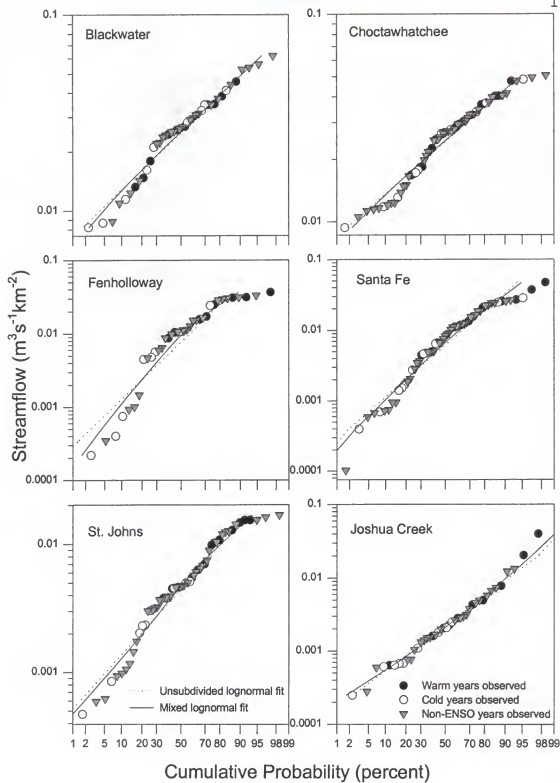


Figure 5.13 Fitted mixed and unsubdivided lognormal distributions to observed streamflows, February

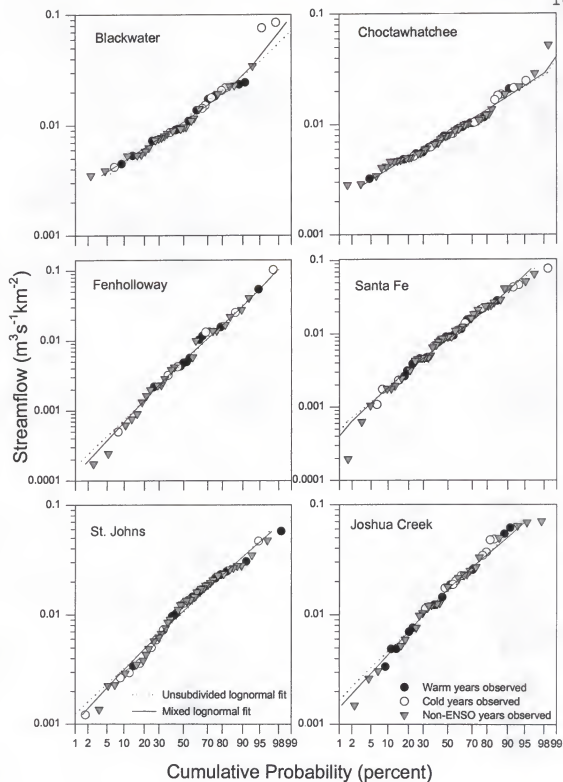


Figure 5.14 Fitted mixed and unsubdivided lognormal distributions to observed streamflows, September

the mixture model provides a means of accomodating, to a certain extent, this more complex form.

Concluding Remarks

Correlations between monthly streamflows and the SOI have been shown to be both significantly negative and positive in the winter and summer high flow periods, respectively. Spatially, the winter relationship is apparent throughout the peninsula, but weakens in the panhandle, and the summer response occurs mainly in northern Florida, including portions of the panhandle. Four probability distributions have been tested for their adequacy in representing the monthly streamflows at each of the gaging stations and it is demonstrated that, while the lognormal provides the best overall fit, it is the mixed lognormal model, based upon the parameters mean and standard deviation, that gives the most complete representation of streamflow across the study area. The improvement in fit is most apparent during the high flow seasons associated with the various winter and summer precipitation regimes.

CHAPTER 6 SPATIAL RESULTS

Spatial patterns of at-a-station results are presented in this chapter. These include correlations between monthly streamflow and SOI, applicability of the lognormal distribution to model the flows, statistical tests assessing differences in means and variances between ENSO conditions, and the mixed lognormal distribution as a potentially more representative model of streamflows. The final section is a discussion of the spatial variability in the observed means and standard deviations from the calibration gaging stations.

Correlations to SOI

Significant negative correlations between monthly streamflow and the SOI are seen fairly consistently across peninsular Florida during the winter season of January-April (figure 6.1). This relationship also exists across northern Florida but for a shorter duration (February and March) while the western panhandle is noticeably lacking in correlations during winter. Positive correlations exist at

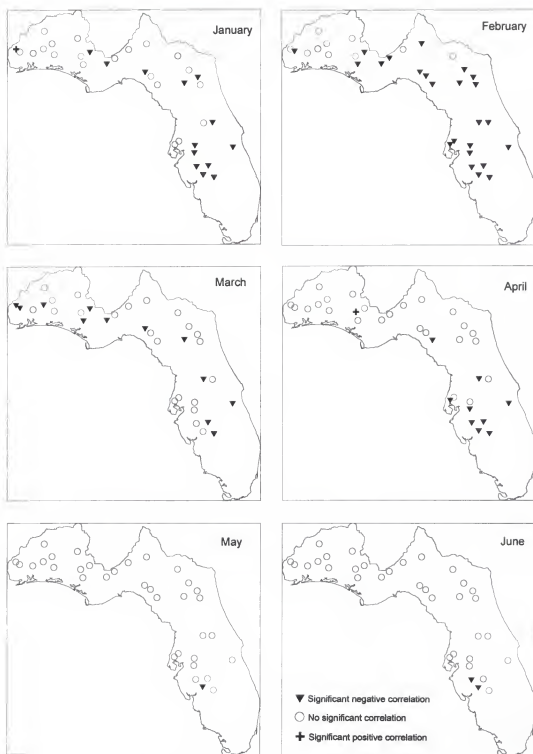


Figure 6.1 Correlation between monthly streamflows and SOI, $\alpha=0.05$

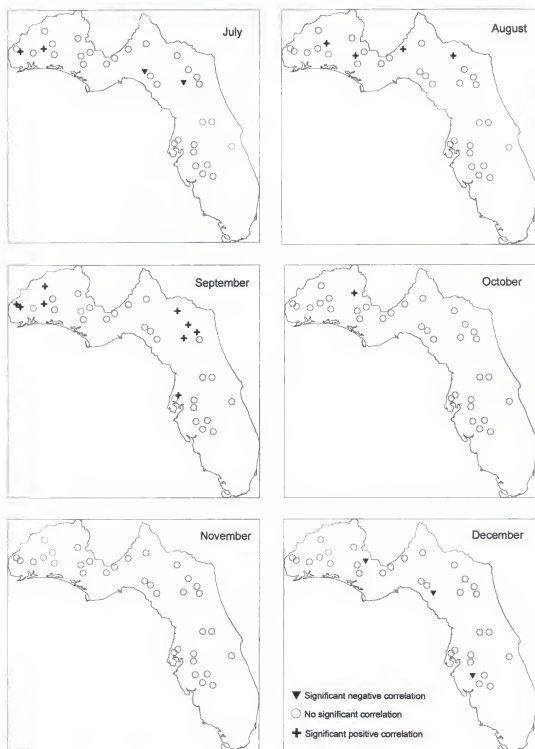


Figure 6.1 -- continued

a few stations in the north from July-September. Whereas they are broadly distributed across the region in August, they are clustered in the western panhandle and northcentral Florida during September. There are two pairs of stations which exhibit correlations during July but they are opposite in sign. The positive pair is located in the western panhandle while the negative pair is situated in the northcentral portion of the state. Stations are not correlated to any extent with the SOI during the transition periods between winter and summer. Thus, the relationship of discharge to ENSO is likely to exist across the peninsula during winter and northern Florida during summer.

Applicability of the Lognormal Model

The lognormal distribution is applicable fairly consistently across the southcentral region of the state throughout the year (figure 6.2), but less so in the panhandle and northcentral regions. For example, it does not perform as well in northcentral Florida during the winter high flow season (January-April), particularly in February, but by April and throughout the remaining seasons and months the model is generally appropriate with the exception of August (yet it performs reasonably well across the remainder of the study area). Across the panhandle the

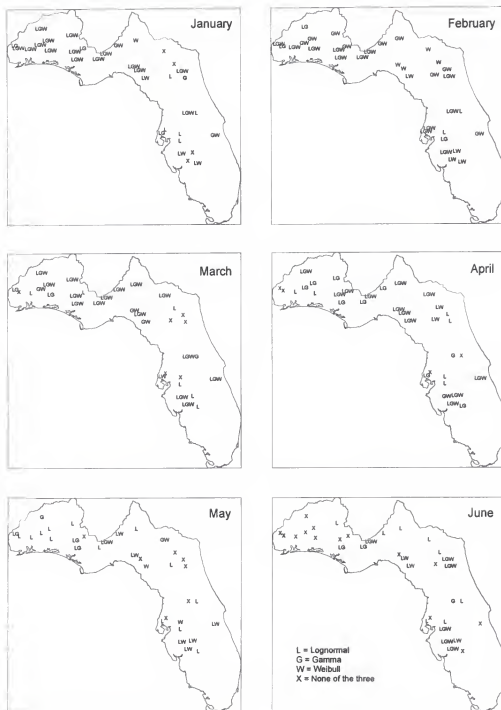


Figure 6.2 Goodness-of-fit of theoretical probability distributions to observed streamflows

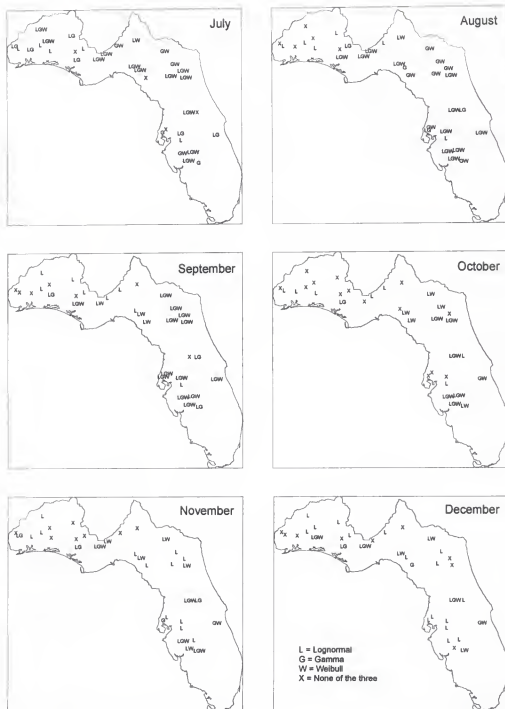


Figure 6.2 -- continued

model tends to be applicable throughout the winter high flow season and into May. During the transition month of June a high proportion of stations situated across the panhandle do not conform to any of the hypothesized distributions. Nevertheless, of the stations that are not significantly different from one of the four hypothesized distributions, it is the lognormal that tends to be more consistently applicable. A similar situation exists during August-September, months of high flow, and October-November, typically transition months, in which there is a high proportion of stations failing to conform to the hypothesized distributions across the panhandle. Again, the lognormal is appropriate for modeling the flows at the remaining stations throughout the region.

F- and t-tests

Under the assumption of lognormality, significant differences in variances and means of flows between warm and cold events are assessed ($\alpha=0.05$) by applying the standard Fisher's F-test and Student's t-test, respectively, to the natural logarithms of flow. Approximately 14.4 percent of the comparisons of variances and 28.8 percent of the means, overall, yield significant differences (figure 6.3). The largest number of differences in variance is recorded during

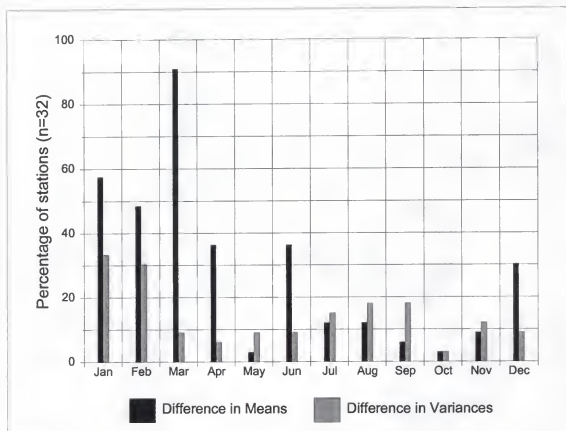


Figure 6.3 Stations exhibiting significant differences between warm and cold years

the winter months of January and February at the outset of the high flow season and during July-September in association with the summer high flow period. Differences in means occur most frequently during January-March although the period extends from December-April, coinciding with the entire winter high flow period. No protracted summer period is readily discernible although slightly more than one-third of the stations indicate significant differences during June.

Mean Monthly Streamflows

Of the winter months, March displays the greatest number of differences throughout the entire study area with only a few exceptions in the panhandle (figure 6.4). Differences occur principally across the peninsula during the remaining winter months. The summer response is in general much weaker. It is at the outset of the summer high flow period in June that the greatest proportion of stations (mostly in southcentral Florida) exhibit significant differences in means. The response diminishes during July and August within this region and it is absent altogether by September. The transition months of May, October and November are similarly lacking in stations with differences in mean streamflows.

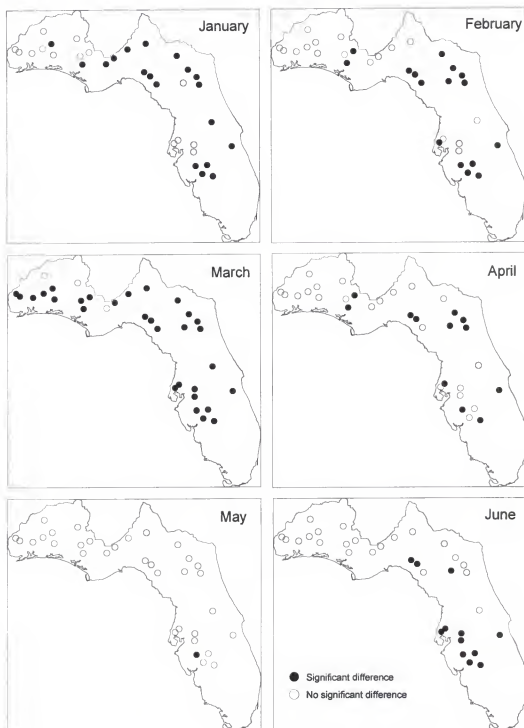


Figure 6.4 Stations exhibiting significant differences in mean monthly streamflows between warm and cold years

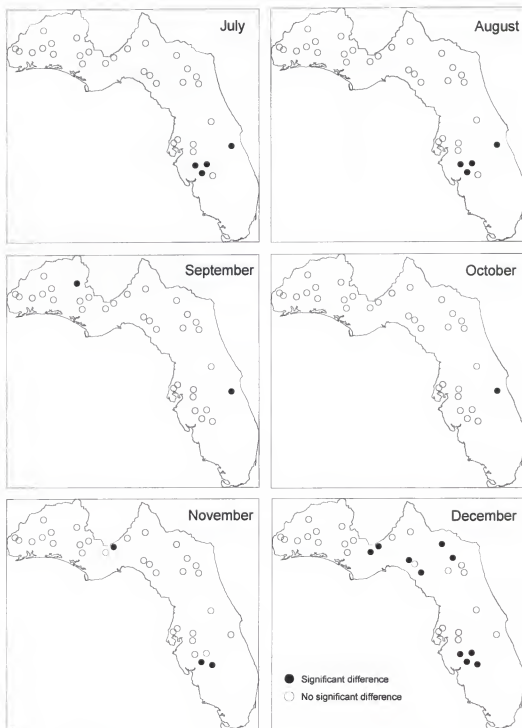


Figure 6.4 -- continued

Variances in Streamflow

Significant differences in the variances between ENSO conditions also occur more frequently in winter, but primarily in January and February (figure 6.5). During January the stations are spread throughout the study area whereas in February they are located only in northern Florida. From the end of the winter season (March-April) through the spring transition period (May-June) there are relatively few stations, which are spatially scattered, exhibiting differences in variance. The southcentral region experiences significant differences during July and August, while differences in the northcentral region occur in September. The response across the panhandle is weak and inconsistent during the summer high flow season; however, the westernmost portion is the only region to display a response during the fall transition, most notably during November.

Mixed Lognormal Distribution

Having demonstrated an effect of ENSO on both the mean of stream flows, primarily during the winter season, and on their variance, during both winter and summer flow periods, the spatial distribution of the applicability of the mixed lognormal model is shown in figure 6.6. Unlike the

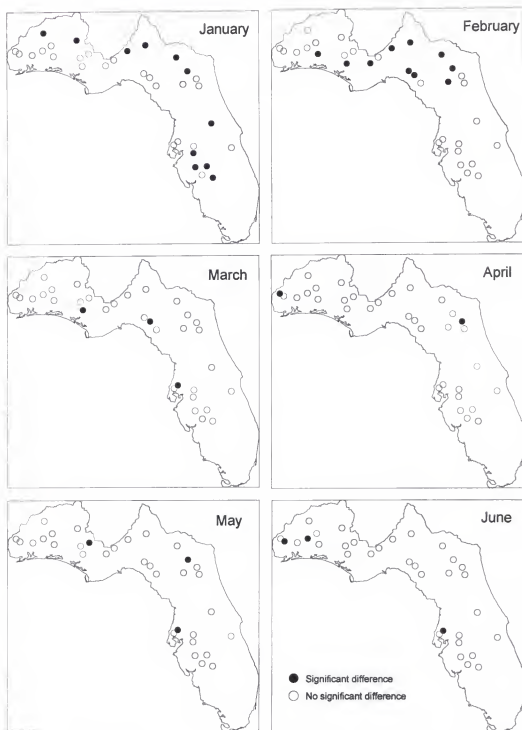


Figure 6.5 Stations exhibiting significant differences in variances of monthly streamflows between warm and cold years

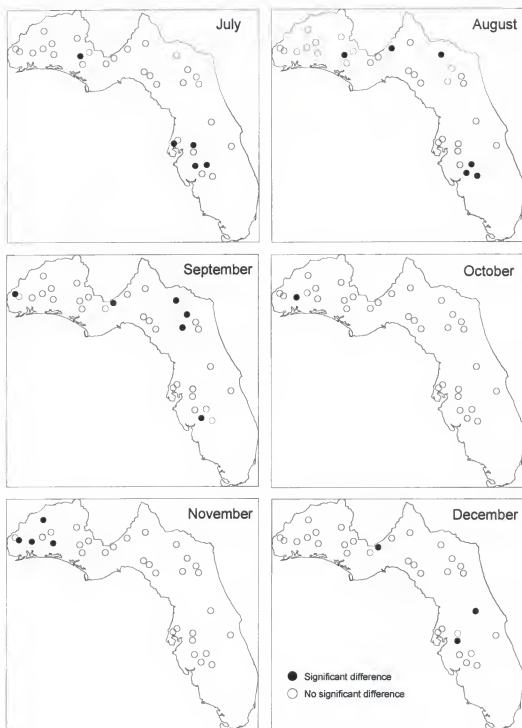


Figure 6.5 -- continued

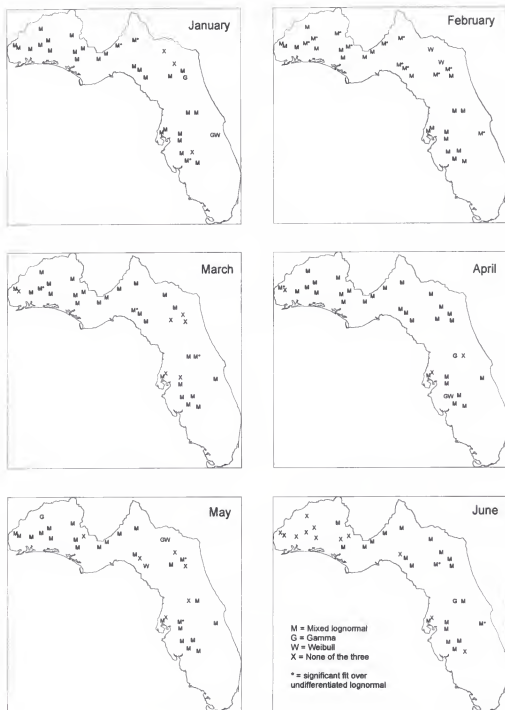


Figure 6.6 Goodness-of-fit of mixture lognormal distribution to observed streamflows

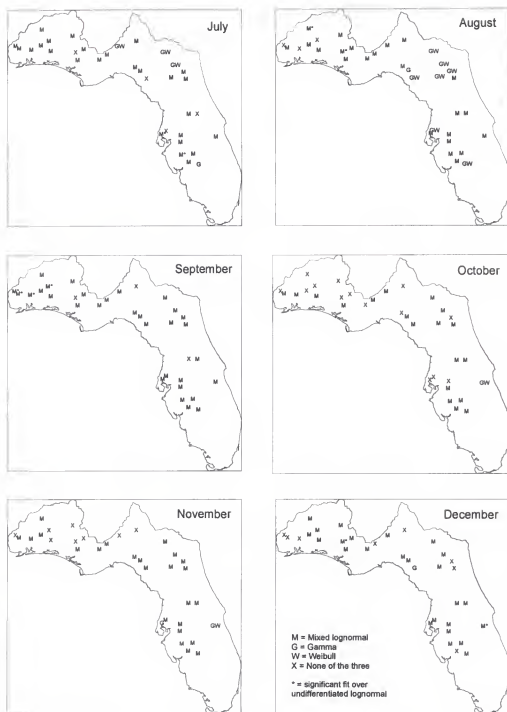


Figure 6.6 -- continued

undifferentiated lognormal model (figure 6.2) the mixture model appears to be appropriate throughout the study region during the winter season (January-April). It also serves to improve modeling of streamflow in peninsular Florida during the transitional May-June period and in the panhandle during the summer high flow period of August-September. Therefore, with the exception of the October-November transition, the mixed lognormal distribution is generally more applicable than the undifferentiated model.

Model Calibration Stations

The spatial variation in mean and standard deviation of streamflow at each of the calibration gaging stations is to be modeled under warm, cold and non-ENSO conditions. Figures 6.7-10 depict the spatial distribution of the observed flows during four months, representative of winter and summer seasons (February and September) and the transition periods between them (May and November).

During February the largest values of runoff occur across the panhandle and decrease toward the southern region (figure 6.7), reflecting the primarily frontal precipitation which emanates from the northwest. By contrast, the largest runoffs occur across the southern portion of the study area during September (figure 6.9), a result of frequent summer

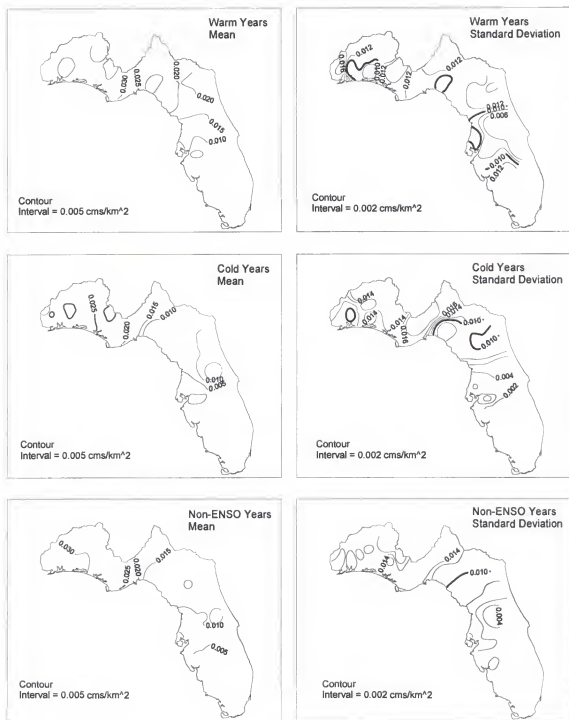


Figure 6.7 Spatial variation in observed mean monthly streamflows, February

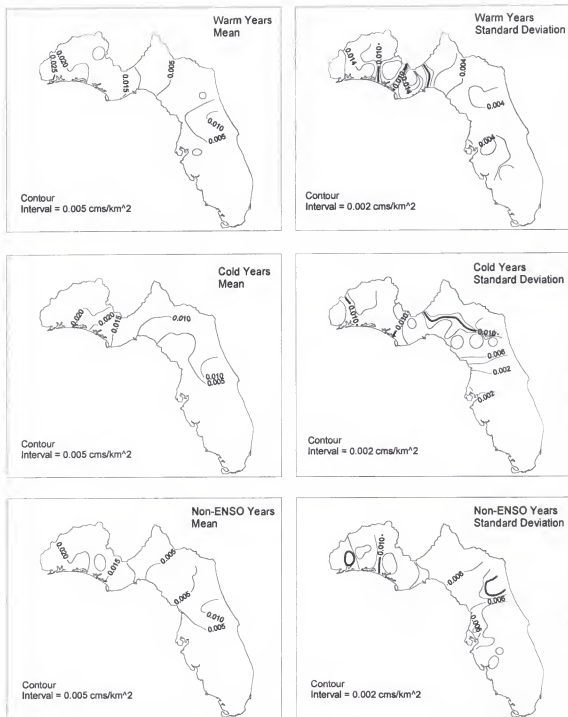


Figure 6.8 Spatial variation in observed mean monthly streamflows, May

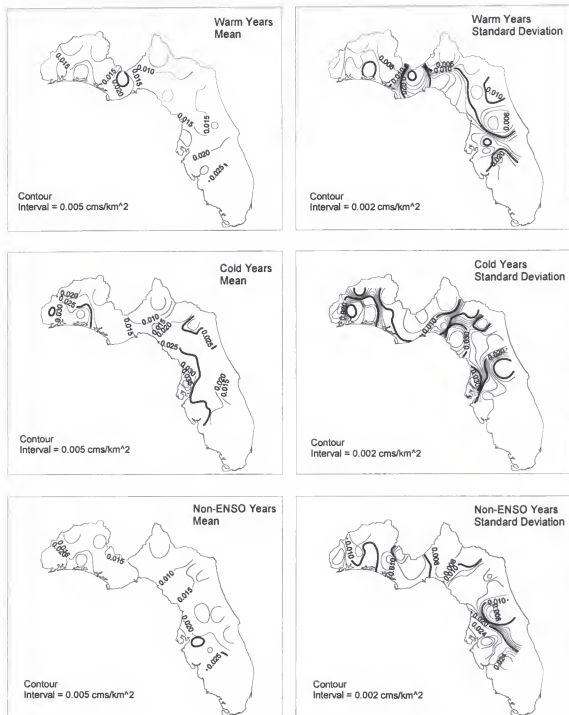


Figure 6.9 Spatial variation in observed mean monthly streamflows, September

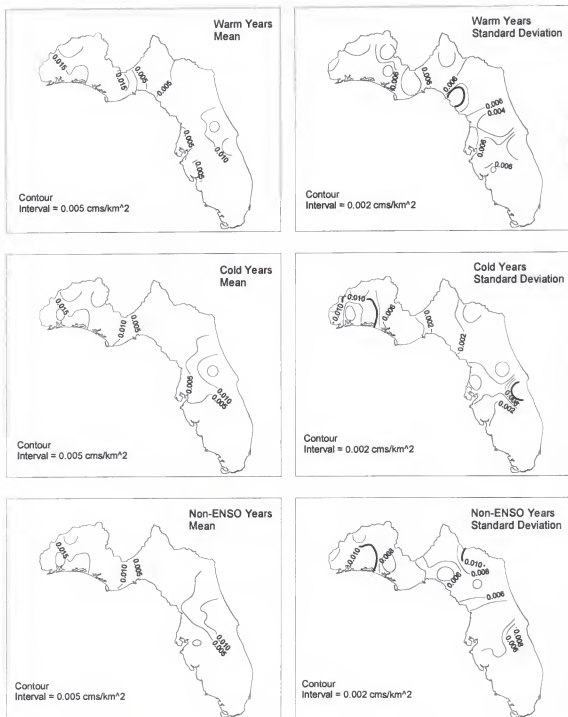


Figure 6.10 Spatial variation in observed mean monthly streamflows, November

convictional storms (Jordan 1984). In general, standard deviations in streamflow are larger in areas with larger means. However, the spatial pattern in these values is more consistent during winter with larger values across the panhandle and smaller values to the south (figure 6.7). In summer there is a wider range in standard deviation with no apparent spatial pattern (figure 6.9).

Winter runoff across the study area is greater during warm years than cold years, with the biggest differences between the two conditions occurring across northcentral Florida (figure 6.7). Advection of moisture and precipitation by the subtropical branch of the jet stream during warm events is in large measure responsible for this pattern across the peninsula (Douglas and Englehart 1981; Ropelewski and Halpert 1987). Although runoff is slightly higher during warm years across the panhandle, the difference between warm and cold conditions is not as great due to the average position of the polar jet stream, which tends to develop a trough to the west of Florida, bringing precipitation to the panhandle during cold events (Hardy 1996).

Summer streamflow is lower during warm years than cold across the western panhandle and much of the peninsula (figure 6.9). In the eastern panhandle (and trending to the northeast) streamflow is either marginally greater during

warm years or nearly identical between ENSO conditions. The spatial pattern in runoff is also less complex during warm events. In general, there is not as wide a range in flows and values are the lowest in northcentral Florida, increasing both westward and southward. By contrast, runoff during cold events is twice that during warm years in the western panhandle and along the western (Gulf coast) peninsula. The dominant precipitation mechanisms operating during the summer are convectional thunderstorms and tropical systems. The literature indirectly suggests the potential for tropical systems to affect Florida to a greater extent during cold events (Gray 1984b; Hastenrath; Poveda and Mesa 1996). In addition, the frequency of hurricane tracks crossing onshore within the study area is greater along the Gulf than the Atlantic coast (Jordan 1984).

During each of the transition periods there is diminished runoff across the study area (figures 6.8,10). Values tend to be higher across the panhandle, decreasing toward the south. An exception to this general pattern is the central peninsula, in which runoff is consistently higher than in surrounding areas. This is the central lakes region in which the effects of storage are reflected in the records of flow. Standard deviations of flow are also

reduced during these periods and the spatial distribution of them is much less complex than during summer.

The spatial variability in observed mean and standard deviation of streamflows is shown to be reasonably grounded in physical interpretation. Spatial patterns of the means tend to be less complex than those of standard deviations, although each increases in complexity during summer. The observed patterns are modeled numerically in a trend surface analysis in the following chapter.

Concluding Remarks

An association between monthly streamflows and the SOI is demonstrated during both winter and summer months. In the former the correlation is negative and spatially dense across peninsular Florida, while those in the latter are positive and present at a lower percentage of stations, located primarily in northern Florida.

The lognormal distribution is more consistently applicable in the southern portion of the study area, although it also performs well across the panhandle during the winter high flow period. Statistical comparisons in means and variances of the log of flows between the warm and cold phases of ENSO indicate that differences in means occur primarily during winter months at stations located across

the peninsula, and that during summer significant differences are located mainly in the southern portion of the study region.

While the lognormal distribution provides a reasonable fit to monthly streamflows during some high flow months and at some locations, the mixed lognormal model gives the most complete representation of streamflow across the study area. The improvement in fit is most apparent in peninsular Florida, particularly in the northcentral region. The mixture model also improves the representation of flows during the winter-summer low flow transition period but fails to do so during the autumnal transition.

CHAPTER 7 SPATIAL MODELING AND PREDICTION

The spatial variation in the parameters mean and standard deviation of streamflow is modeled across the study region. Three trend surfaces (1st, 2nd and 3rd order) are fit to the parameters for each month and climatic condition. Goodness of fit measures and analysis of residuals are discussed. Surfaces from four months, representing the winter and summer regimes and the transition periods between them, are selected for a detailed discussion. Upper and lower confidence surfaces (95 percent level) are also generated for each trend. The chapter concludes with the prediction of streamflows at four test stations based upon the calibration stations of the trend surface models.

Trend Surface Models of Streamflow

First, second and third order trend surfaces are generated to model the spatial variability of means and standard deviations of observed streamflows under warm, cold and non-ENSO climatic conditions, respectively. Fisher's F-statistic is used to assess the goodness of fit ($\alpha=0.05$) of

a particular trend surface to the spatial variability in a given parameter. A modification of the F-statistic is also used to assess the significance of improvements of higher order surfaces. Results are summarized in tables 7.1 and 7.2.

Goodness of Fit

A 2nd order trend surface provides a significant fit to mean runoff for all months and climatic conditions (table 7.1). By contrast, the 1st order surface is not adequate in October for the non-ENSO conditions, nor is it significant in September for the cold years subpopulation. The 2nd order surface offers significantly increased explanatory power beyond the 1st order for five months during warm years, nine months during cold years, and ten months during non-ENSO conditions. A 3rd order surface provides significant fits for most months and conditions; however, it fails to offer any additional explanatory power beyond that of the 2nd order surface. Therefore, the 2nd order surface proves to be the most adequate in modeling the variation in mean runoff across the study area.

The spatial variation in standard deviation of flows during warm years is modeled best by a 2nd order surface only failing to provide a significant surface only during August and November (table 7.2). By contrast, a 1st order

Table 7.1 Results of trend surface analyses: Mean streamflow

Order of Surface	WARM YEARS			COLD YEARS			NON-ENSO YEARS		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
JAN	*	*	*	*	*†	*	*	*†	*
FEB	*	*	*	*	*	*	*	*†	*
MAR	*	*	*	*	*†	*	*	*	*
APR	*	*	*	*	*†	*	*	*†	*
MAY	*	*†		*	*	*	*	*†	*
JUN	*	*	*	*	*†	*	*	*†	*
JUL	*	*	*	*	*†	*	*	*	*
AUG	*	*†	*	*	*	*	*	*†	*
SEP	*	*	*		*†	*	*	*†	*
OCT	*	*†	*	*	*†			*†	*
NOV	*	*†	*	*	*†	*	*	*†	*
DEC	*	*†	*	*	*†	*	*	*†	*
Significant Surface	12	12	11	11	12	11	11	12	12
Significant Improvement	n.a.	5	0	n.a.	9	0	n.a.	10	0

* denotes significant trend surface ($\alpha=0.05$)

† denotes significant improvement upon lower order surface

n.a. denotes not applicable

Table 7.2 Results of trend surface analyses: Standard deviation of streamflow

Order of Surface	WARM YEARS			COLD YEARS			NON-ENSO YEARS		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
JAN		*†		*	*	*	*	*	*
FEB		*†		*	*	*	*	*	*
MAR		*†		*	*†	*	*	*†	*
APR	*	*	*	*	*	*	*	*	*
MAY	*	*	*	*	*	*	*	*	*
JUN	*	*†		*	*	*	*	*	*
JUL	*	*	*	*	*†		*	*	*
AUG				*	*		*	*†	*
SEP	*	*			*†		*	*†	*
OCT	*	*		*			*	*	
NOV				*	*†	*	*	*†	*
DEC	*	*	*	*	*	*	*	*†	*
Significant Surface	7	10	4	11	11	8	12	12	11
Significant Improvement	n.a.	4	0	n.a.	4	0	n.a.	5	0

* denotes significant trend surface ($\alpha=0.05$)

† denotes significant improvement upon lower order surface

n.a. denotes not applicable

surface is significant in only seven months and the fit of a 3rd order surface in only four months. Both 1st and 2nd order surfaces are significant for eleven months during cold events and all twelve months during non-ENSO years, yet the 2nd order surface offers explanatory power beyond the 1st order in four months during warm and cold events and five months under non-ENSO conditions. The 3rd order surface again offers no additional explanatory power beyond that of the 2nd order. Thus, the 2nd order surface also best models the spatial variation in the standard deviation of runoff.

A representative value of observed variation in mean or standard deviation of runoff explained by the fitted surface is provided by the adjusted R^2 (figures 7.1 and 7.2). No less than 75 percent of the variation in mean runoff is accounted for by a 2nd order trend surface from November-May under each of the three conditions (figure 7.1). The variation in means explained under warm climatic conditions decreases to below 40 percent in June and is between 44-59 percent during July-November. By contrast, the variation explained under cold conditions remains relatively high through July. Lowest values occur during August-October (between 37 and 49 percent). Non-ENSO conditions display the poorest fits from July-October (between 45 and 61 percent).

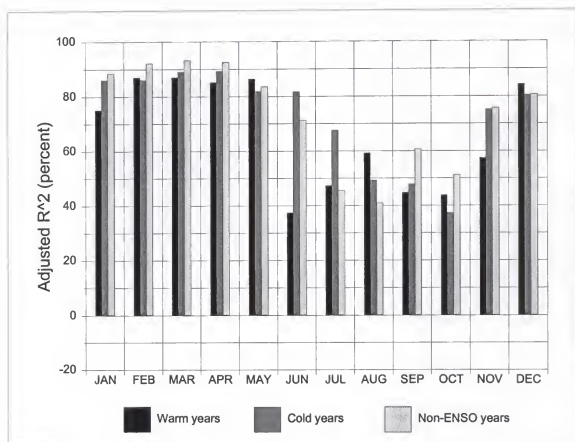


Figure 7.1 Adjusted R^2 values for 2nd order trend surfaces of mean monthly runoff

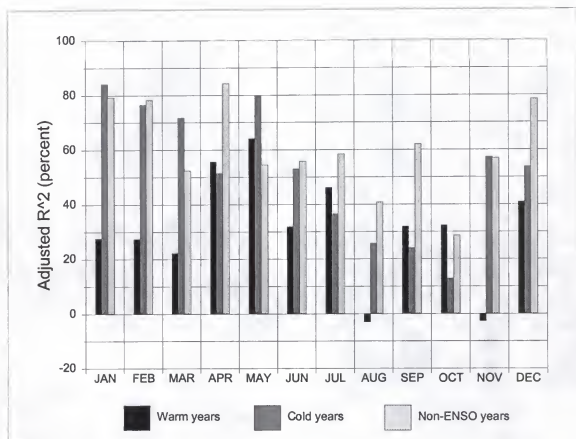


Figure 7.2 Adjusted R^2 values for 2nd order trend surfaces of standard deviation in monthly runoff

In general, adjusted R^2 values are lower for standard deviations of runoff because of the nature of estimating the second moment (squaring deviations about the mean) in conjunction with reduced sample sizes. The variation in standard deviations of runoff is, like that of the means, modeled best during the winter season (figure 7.2).

Although the fits are significant, as previously discussed, the adjusted R^2 percentages during warm years are between 22 and 28 from January-March. Only during one month (May) is the adjusted R^2 greater than 50 percent. The spatial variability in standard deviation cannot adequately be modeled by a 2nd order trend surface during August and November and this is confirmed by the negative adjusted R^2 values corresponding to these months. Cold years yield adjusted R^2 values of greater than 50 percent from November-June. The lowest occurs in October (13 percent), the only month in which the 2nd order surface is not significant under this climatic condition. Non-ENSO years have adjusted R^2 greater than 50 percent during all months except August and October, yet the fit of the 2nd order surface is significant.

Streamflow is generally modeled by a 2nd order trend surface better during the winter high flow season than during the summer. The October-November transition period tends to be the weakest period for modeling the mean flows

while August-October is the weakest for the standard deviations in flow.

Analysis of Residuals

Analysis of residuals of the 2nd order trend surfaces is performed in order to determine whether there is a potential violation of the underlying assumptions of the model. Specifically, plots of standardized residuals versus predicted runoff and standard deviation of runoff (appendix B) are examined by testing for independence and normality of the error terms. Homoscedasticity (constant variance in the residuals with all levels of the predicted parameter) is checked by visually examining these graphs.

In no case is there evidence to suggest that the residuals are correlated with the predicted parameters ($\alpha=0.05$); thus, the assumption of independence cannot be said to be violated. The hypothesis of normality ($\alpha=0.20$) of the residuals of standard deviation of runoff is rejected only for the month of December during cold events. The remaining months cannot be said to deviate significantly from normal. Regarding the means, no month or condition violates the assumption of normality. Finally, a visual inspection of the plots shows that the variance of the residuals does not tend to consistently increase or decrease with increasing values of the predicted parameters.

Therefore, given that the 2nd order trend surfaces model the parameters satisfactorily and that they generally conform with the underlying assumptions of ordinary least squares regression, they can be used as the bases of predicting the parameters at test sites within northcentral Florida.

2nd order trend surfaces

Spatial variability in the means and standard deviations of flow are shown to be best modeled by 2nd order trend surfaces. Parallel to the discussion of observed flows in the preceding chapter, these surfaces are portrayed in figures 7.3-6 for February and September (winter and summer seasons) as well as May and November (transition periods between the two flow regimes).

The patterns of runoff during February indicate higher flows in the panhandle, decreasing to the south (figure 7.3). Highest values in the range of $0.015 \text{ m}^3\text{s}^{-1}\text{km}^{-2}$ and greater are confined to the panhandle during cold events but they penetrate throughout northcentral Florida during warm events. These surfaces mirror the observed flows (figure 6.7) fairly well, evidence of which is reflected in the relatively high adjusted R^2 values. The general trend of decreasing runoff during warm years is NW-SE. During cold events there seems to be two trends evident. One is situated in the north whereby the flows decrease in a more

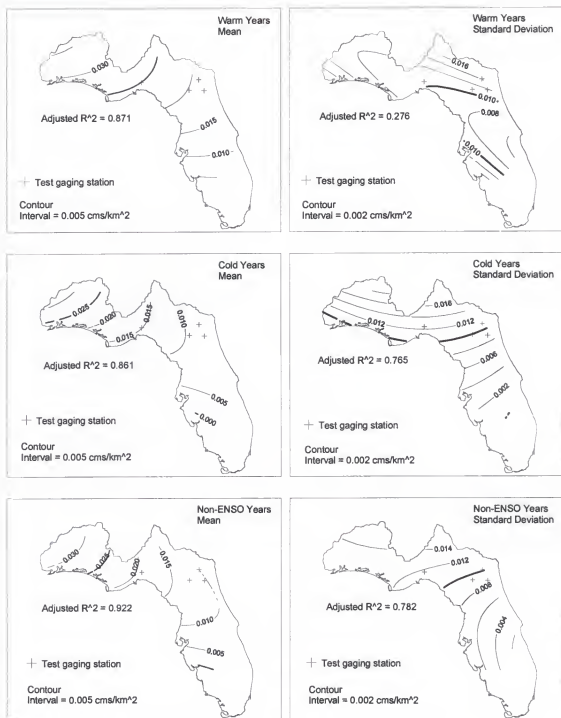


Figure 7.3 Second order trend surfaces fit to observed means and standard deviations of runoff, February

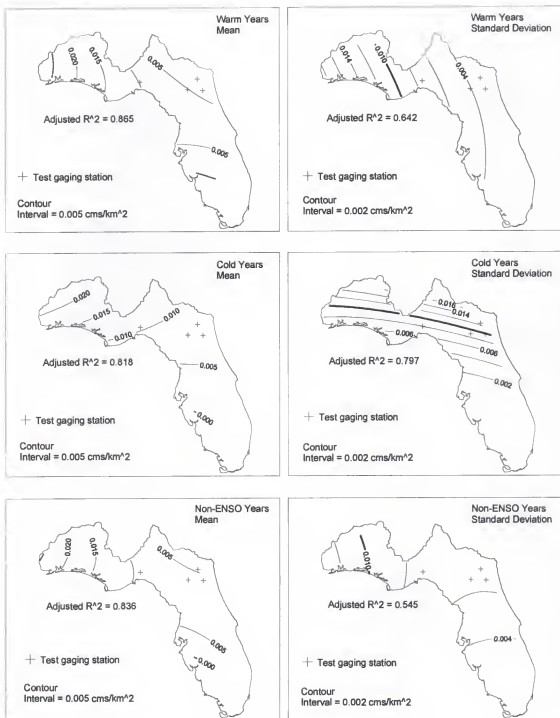


Figure 7.4 Second order trend surfaces fit to observed means and standard deviations of runoff, May

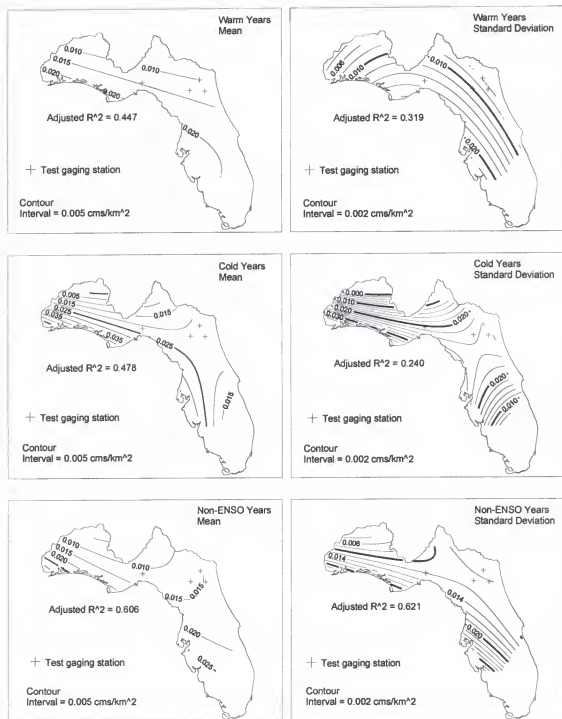


Figure 7.5 Second order trend surfaces fit to observed means and standard deviations of runoff, September

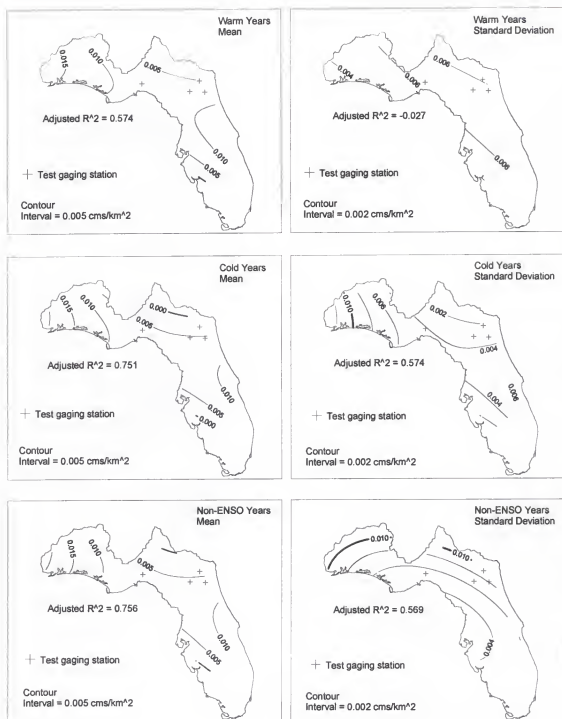


Figure 7.6 Second order trend surfaces fit to observed means and standard deviations of runoff, November

W-E direction and the other is in the southern region in which they decrease toward the southwest. The same general pattern is seen in the standard deviations during cold and non-ENSO events. During warm events the trend surface fits the observed standard deviations poorly (note the low adjusted R^2).

Trend surfaces account for approximately 45 percent of the variation in September runoff during warm and cold events (figure 7.5) and about 60 percent of the variation during non-ENSO conditions. Similar to the observed means (figure 6.9) the greatest contrasts between warm and cold events occur along the Gulf coast. Runoff throughout northcentral Florida is higher during cold years, but it is more consistent throughout the region than in warm years. Standard deviations in general reflect the patterns of means. During cold years steeper gradients are modeled in the panhandle and southern regions with more consistent behavior shown across northcentral Florida. The pattern during warm years suggests a more uniform change from higher values along the Gulf coast to lower values in the north and along the Atlantic coast. These surfaces, however, are explaining only 24 and 32 percent of the variation in standard deviations during cold and warm years, respectively, as the observed values are spatially complex across the study region.

Trend surfaces of means in May and November indicate that flows are highest in the panhandle and decrease toward the south (figures 7.4 and 7.6). Virtually no difference between warm and cold events exists in November throughout the entire study area. In May the northcentral region displays the greatest differences with runoff in cold years nearly twice that of warm years. The panhandle and southern regions reflect similar patterns in means, showing little change between warm and cold events.

The patterns of standard deviation are markedly different between warm and cold events in both months. The model of warm years in May indicates the highest values are located in the western panhandle and that they decrease in an easterly direction. By contrast during cold events the largest values are situated across the northern portion of the study area and they decrease toward the south. During cold years northcentral Florida displays values that are more than twice those of warm years while the southern region exhibits fairly small standard deviations under both sets of conditions. In November the model for cold years indicates the largest values in the panhandle and southeast with a saddle of low standard deviations across northcentral Florida. The pattern for warm years displays little change, but the model is unable to effectively replicate the

observed data, as reflected in the negative adjusted R^2 for the surface.

Confidence Surfaces

Second order trend surfaces have been demonstrated to reasonably model monthly streamflows across the study region under each of the climatic conditions. Confidence surfaces ($\alpha=0.05$) are generated for each of the trend surfaces as a basis for assessing the fits in a qualitative manner and, more importantly, for use as predicting devices beyond the original trends. Qualitatively, the lower confidence surfaces about the fitted trends are not so broad as to include negative values of streamflow, even during transition periods that are typically characterized by lower values of runoff. They also tend to mirror the original trend, although deviations occur due to the fact that the gaging stations are not evenly distributed (figure 7.7). Since they represent intervals about the trend surfaces their greatest utility is in the generation of upper and lower estimates of parameters.

Test Stations and Prediction of Streamflows

Four test sites, not previously used in the analysis but with periods of record ranging from 23-35 years, have been selected from northcentral Florida in order to test the

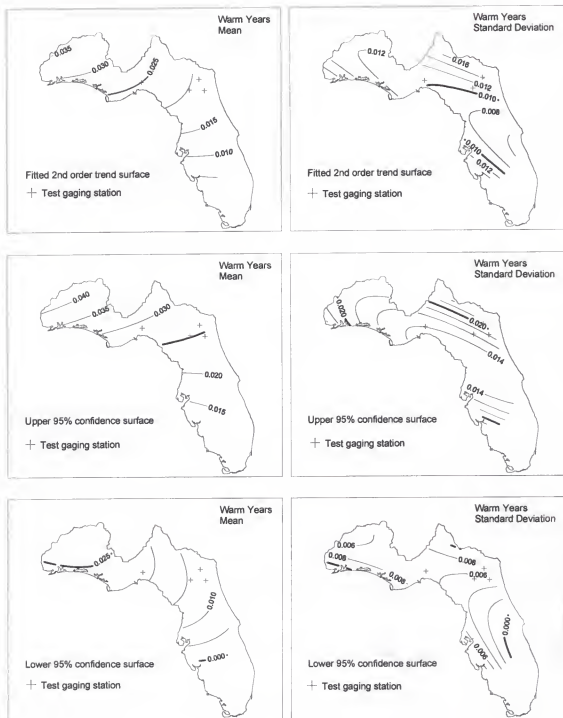


Figure 7.7 Second order trend surfaces and upper and lower confidence surfaces, February

efficacy of the proposed procedure (figure 7.8). Expected monthly means and variances for each month are calculated from the appropriate trend surfaces, employing the centroid of each basin. In order to assess the accuracy of the estimates of means, they are compared with the 90 and 95 percent confidence intervals about the observed means for each month and subpopulation. These estimates are then substituted into the mixed lognormal models (generated from the three subsets of climatic conditions) and anticipated probability distributions of flows are generated for all months. Three methods of assessing the predictions are employed, including 1) the standard Kolmogorov-Smirnov goodness of fit test, 2) estimation of the likely ranges of parameters based on the 95 percent confidence surfaces and 3) the calculation of 95 percent confidence intervals about the computed cumulative probability distribution.

Observed and Predicted Means at Test Sites

Mean streamflows and their standard deviations are calculated from the observed data for each of the four test stations. The standard errors of the estimates are used to construct both the 90 and 95 percent confidence intervals about the means for each of the climatic conditions. Predicted means from the 2nd order trend surfaces are plotted along with the observed means and confidence

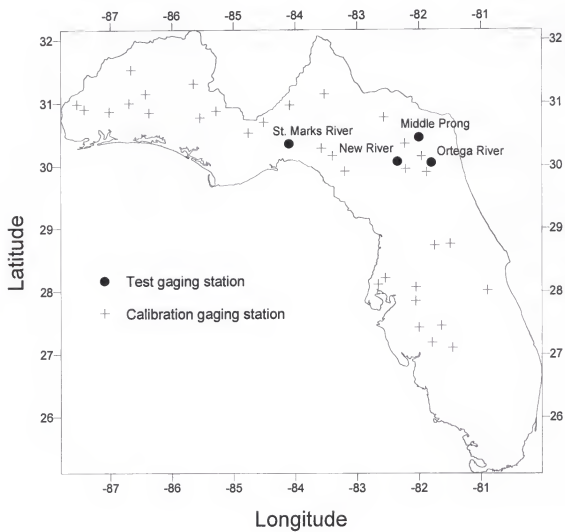


Figure 7.8 Location map of test basin centroids

intervals in figures 7.9-12. Estimates derived from the surfaces lie within the 90 percent confidence intervals under most conditions and months. In general, estimates of mean streamflows tend to lie outside of the confidence bounds when the limits are within a tight range (i.e., when the standard deviations are small).

Winter-Spring (December-May)

Three of the four test stations (Middle Prong, Ortega and New rivers) provide reasonable predictions for most months and conditions (figures 7.9-11). The poorest estimates occur in December on the Middle Prong under cold conditions and New river during non-ENSO conditions, and in May on the Middle Prong in warm years and Ortega river in cold years. With the exception of these cases, the trend surface models of monthly means seem to provide reasonable estimates for these three rivers. In contrast, the St. Marks is consistently poor throughout most of the period (figure 7.12). Streamflow is overestimated in four of the six months under warm and non-ENSO conditions.

Summer-Fall (June-November)

July, August and October provide predictions that lie within the 90 percent confidence intervals for each test station and climatic condition. In the remaining three months, estimates are the poorest during cold years. Predictions are outside of the 90 percent bounds in June for

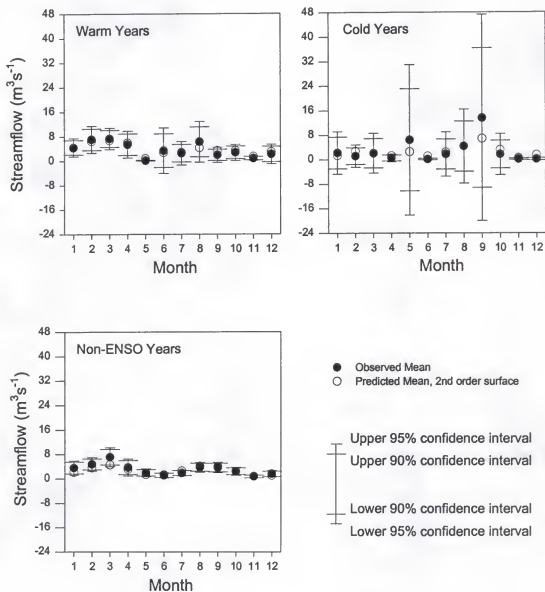


Figure 7.9 Predicted and observed mean streamflow with confidence intervals, Middle Prong

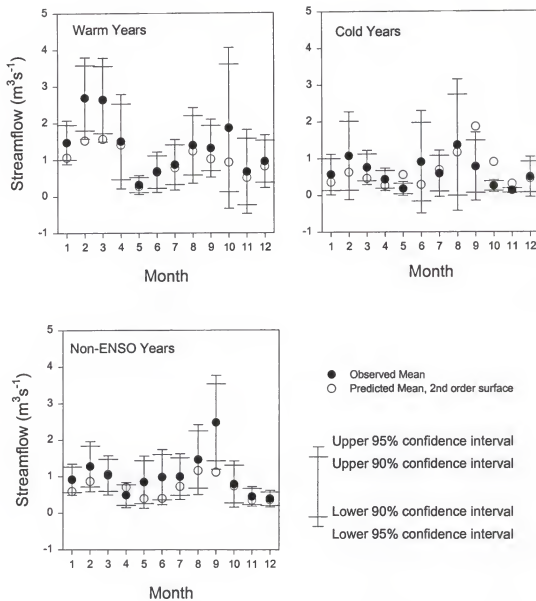


Figure 7.10 Predicted and observed mean streamflow with confidence intervals, Ortega River

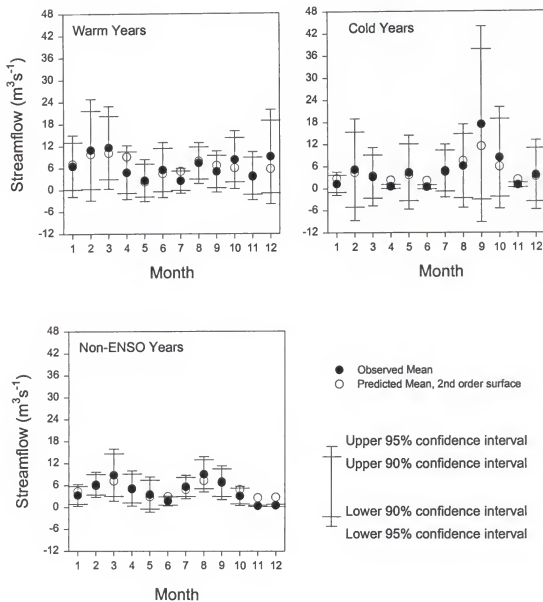


Figure 7.11 Predicted and observed mean streamflow with confidence intervals, New River

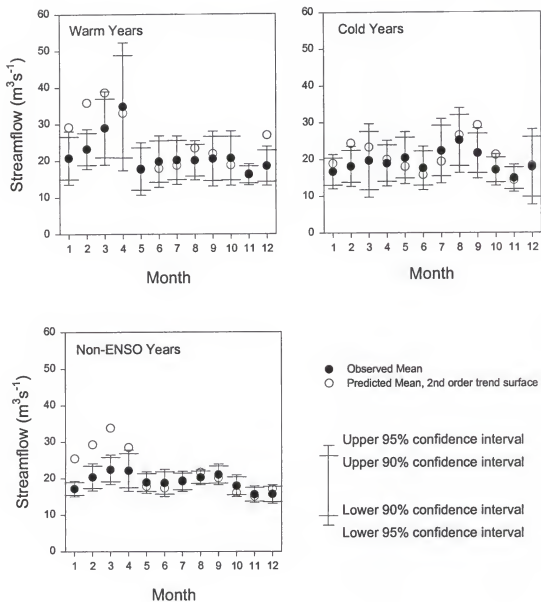


Figure 7.12 Predicted and observed mean streamflow with confidence intervals, St. Marks

the Middle Prong and New river, September for the Ortega and St. Marks rivers, and November at the Middle Prong, Ortega and New rivers. Estimates are also poor during non-ENSO years in September and November for the Ortega and New rivers, respectively. Predicted means are within the 90 percent bounds during warm events for all months in this season with only one exception (November, Middle Prong).

Predicted Lognormal Models

Predicted mixed lognormal distributions are generated for each month based upon estimates derived from 2nd order trend surfaces for each subpopulation. The Kolmogorov-Smirnov test indicates that the mixture model performs poorly on all four rivers with perhaps the best results on the Ortega river for which an adequate fit is obtained in only four months (table 7.3). The technique provides adequate fits for the Middle Prong in only two months, the St. Marks in one month, and not at all for the New river.

95 percent confidence surfaces

Estimates of means and standard deviations from the upper and lower 95 percent confidence surfaces are combined in four ways in order to provide some indication of variations in distributions that might be reasonable to expect. By using these estimates improvement in fit occurs at all four test stations (table 7.3). In general the

Table 7.3 Predicted mixed lognormal distribution

	Middle Prong	Ortega River	New River	St. Marks River
JAN		HH, HL		
FEB	* HH, HL	HH, HL	LL	
MAR	HH, HL	HH, HL		LH, LL
APR	LH, LL	* LH, LL		* HH, HL
MAY				
JUN	LL	*		
JUL				
AUG	*	* HH		
SEP	LH	HH	LH	
OCT				
NOV		LH, LL		
DEC	LL	* LL		

* = Fail to reject H_0 : of lognormality - predicted function from trend surfaces

HH = Fail to reject H_0 : - from 95% confidence surfaces, high mean and standard deviation

HL = Fail to reject H_0 : - from 95% confidence surfaces, high mean, low standard deviation

LH = Fail to reject H_0 : - from 95% confidence surfaces, low mean, high standard deviation

LL = Fail to reject H_0 : - from 95% confidence surfaces, low mean and standard deviation

greatest improvement occurs for the Middle Prong and Ortega river. Results are only marginally better for the New and St. Marks rivers. Adequate fits are obtained for the Ortega river in nine months and in seven months for the Middle Prong. Seasonally, the model performs best during the winter-spring period. This technique provides adequate fits for the Ortega river from December-April and they are nearly as good for the Middle Prong (which fails in January). During the summer-fall seasons improvement beyond the fitted trend surface occurs in September for three test stations and in June and November at one station each. The model fails at all four stations during May, July and October.

Probability plots of the predicted mixed lognormal distributions are presented in figures 7.13-16. In general, the model fits the observed data better at higher streamflows throughout the year for the Middle Prong and New River (figures 7.13 and 7.15). The distribution models high flows of the Ortega river (figure 7.14) reasonably well during summer (July-September) but performs better for lower flows during winter (December-April). The model is poor during all months for the St. Marks (figure 7.16).

It appears that estimates of the mean are generally within reasonable bounds of the observed data, but that there is a general failure in the ability to model the variability in streamflow, particularly a tendency to

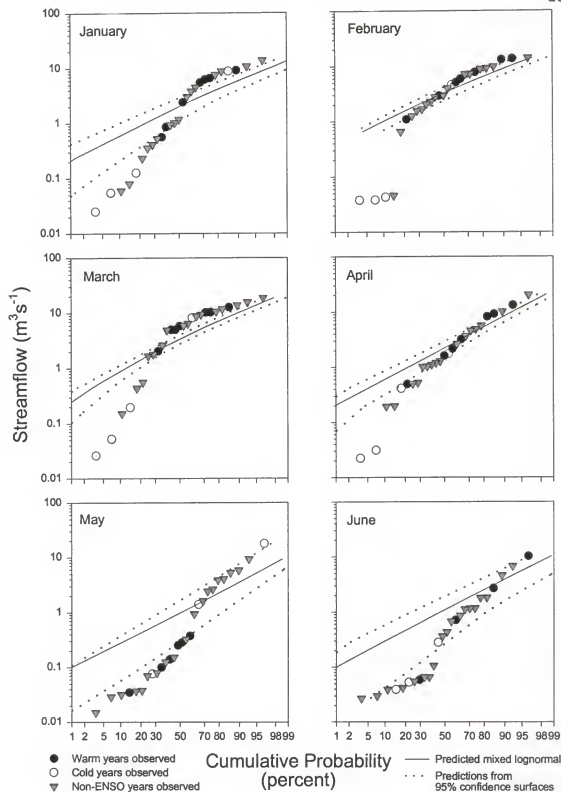


Figure 7.13 Predicted mixed lognormal distributions, Middle Prong

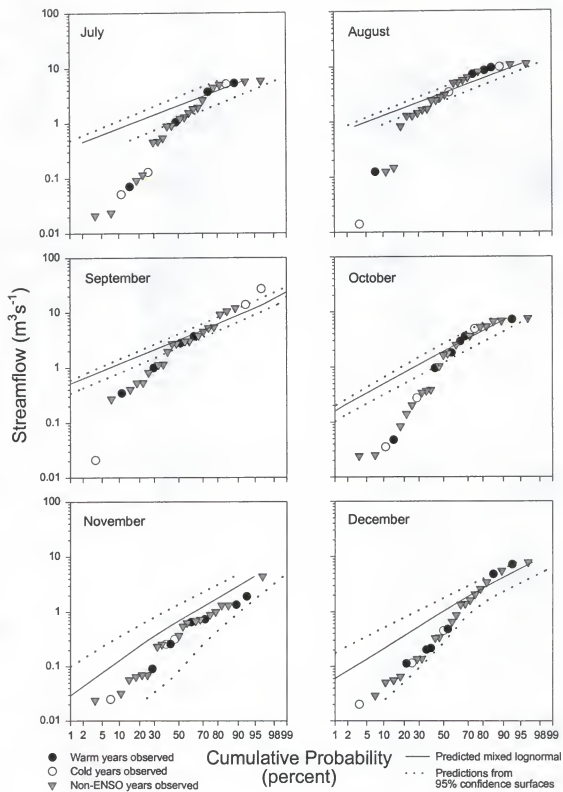


Figure 7.13 -- continued

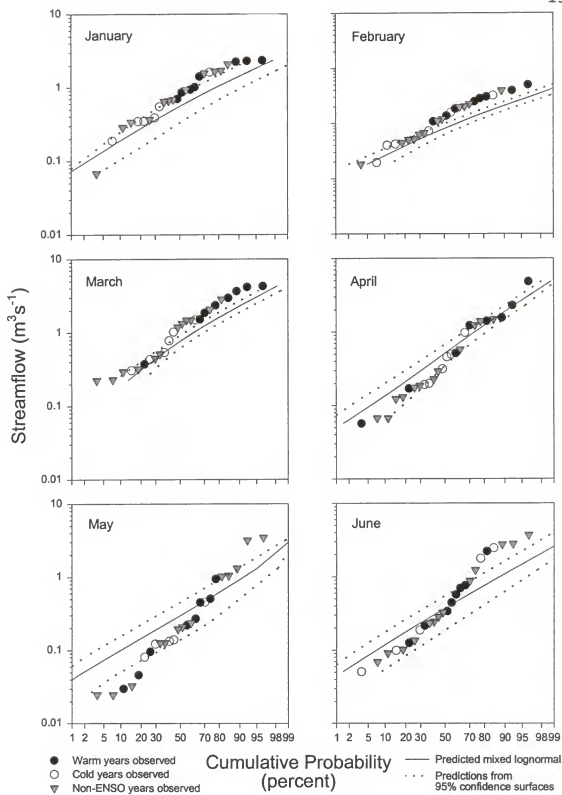


Figure 7.14 Predicted mixed lognormal distributions, Ortega River

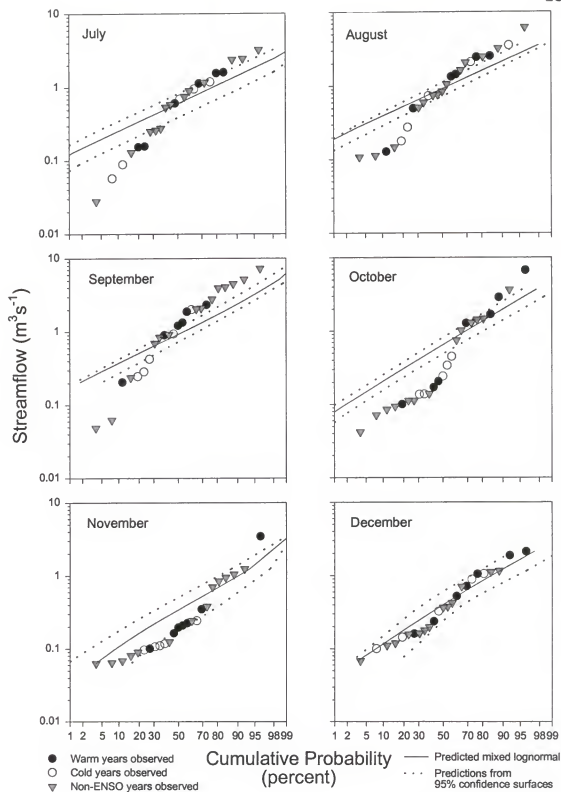


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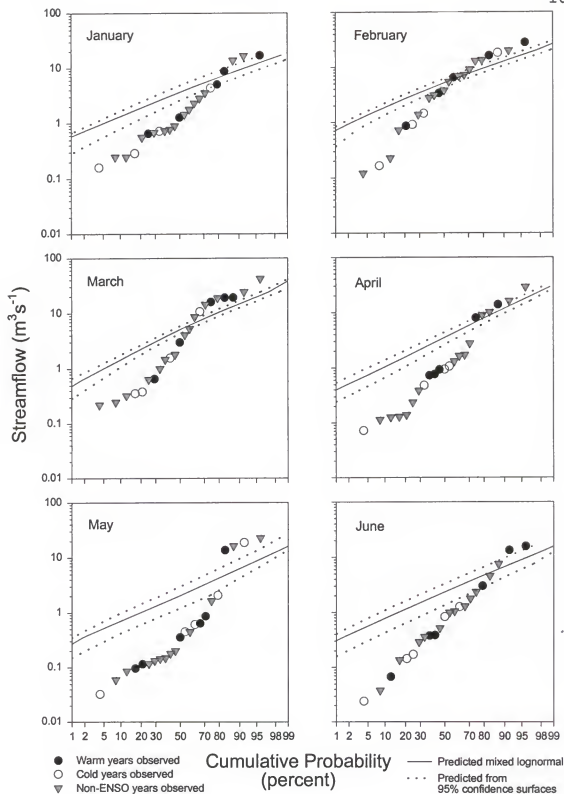


Figure 7.15 Predicted mixed lognormal distributions, New River

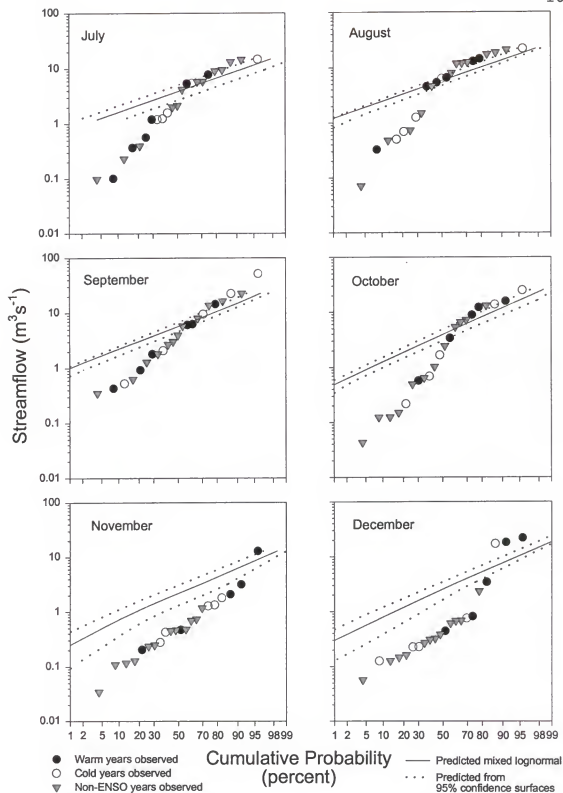


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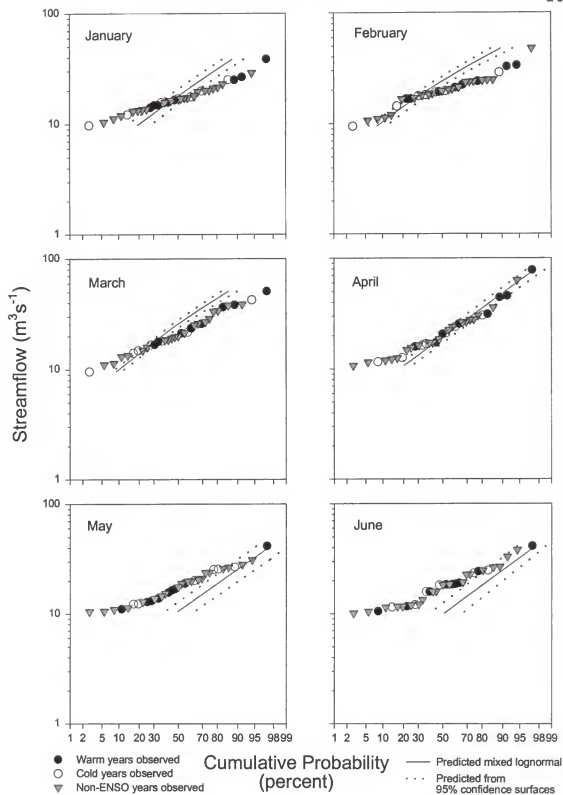


Figure 7.16 Predicted mixed lognormal distributions, St. Marks

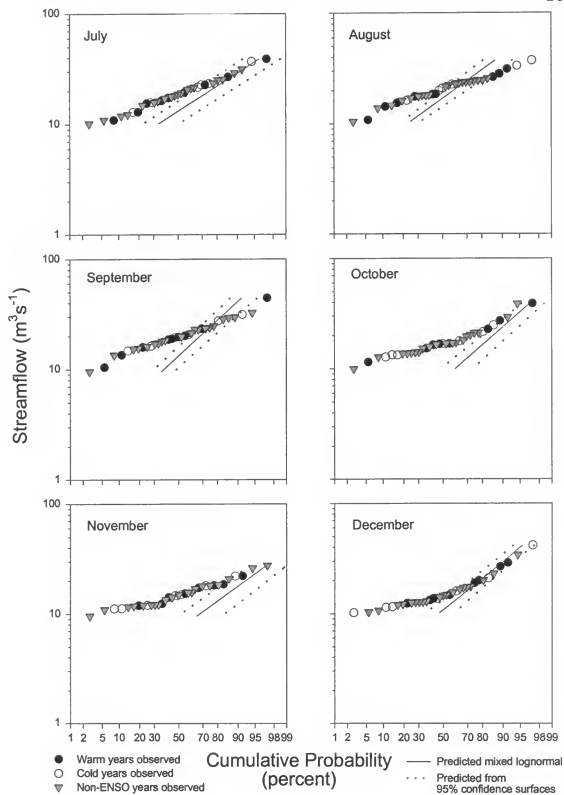


Figure 7.16 -- continued

underestimate variances. The exception to this general trend is the St. Marks.

95 percent confidence bounds about the fitted function

In addition to the construction of distributions based upon the parameters from the confidence surfaces, 95 percent confidence intervals are constructed about the cumulative probability distributions estimated from the 2nd order trend surfaces. The underlying premise is that 95 percent of the estimates will lie within two standard deviations of the most probable value of cumulative probability (the predicted function). Confidence intervals for the mixture model are presented in figures 7.17-20. Results show that small streamflows are incorporated within the interval in all months on the Ortega river, but it fails to include high flows during summer and fall (figure 7.18). By contrast, confidence intervals for the Middle Prong fail to include low discharges for nearly every month as well as the central portion of the distribution in May and June, which are typically transition months when flows are low (figure 7.17). In general, observed high flows tend to be incorporated within the confidence intervals. The St. Marks is an exception in which the intervals fail to incorporate the majority of flows (figure 7.20).

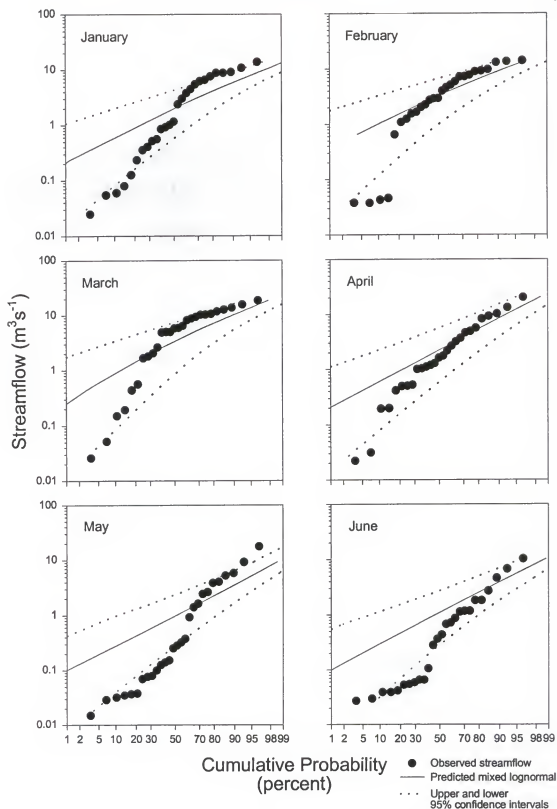


Figure 7.17 Predicted mixed lognormal distribution and confidence intervals, Middle Prong

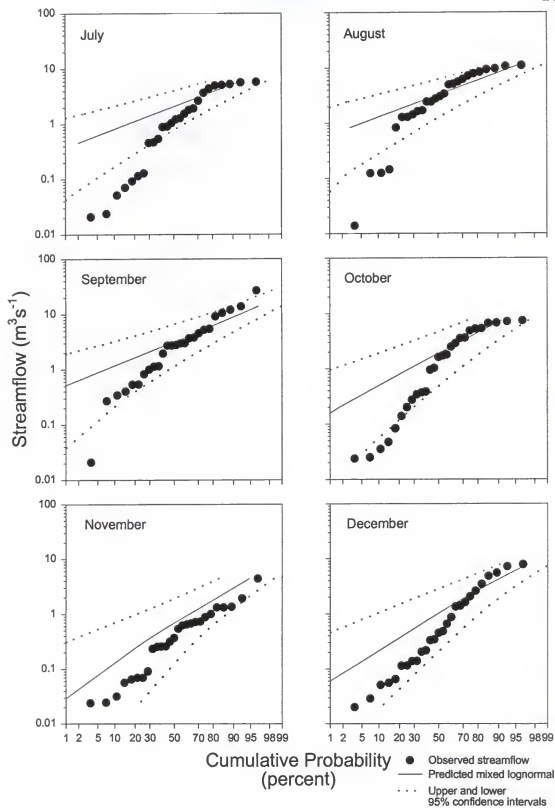


Figure 7.17 -- continued

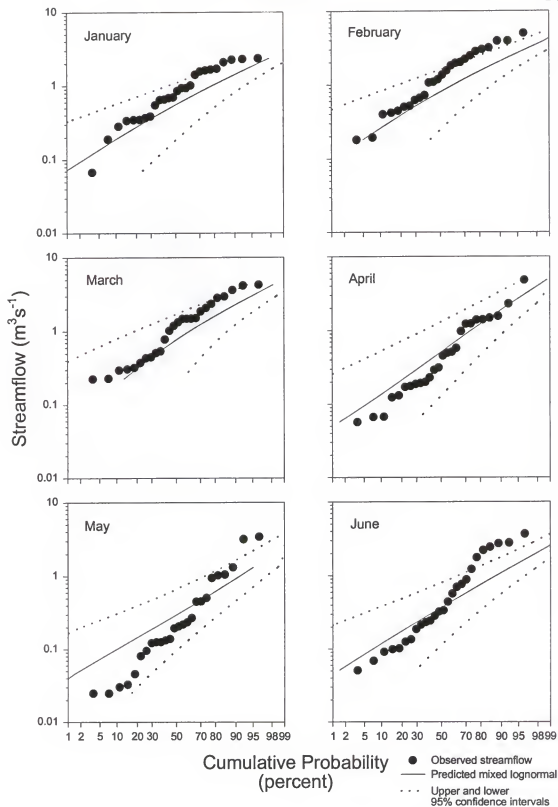


Figure 7.18 Predicted mixed lognormal distribution and confidence intervals, Ortega River

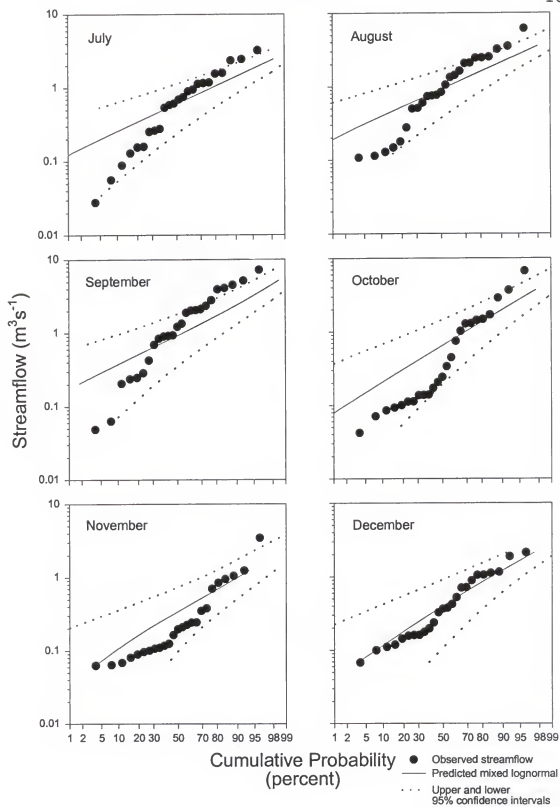


Figure 7.18 -- continued

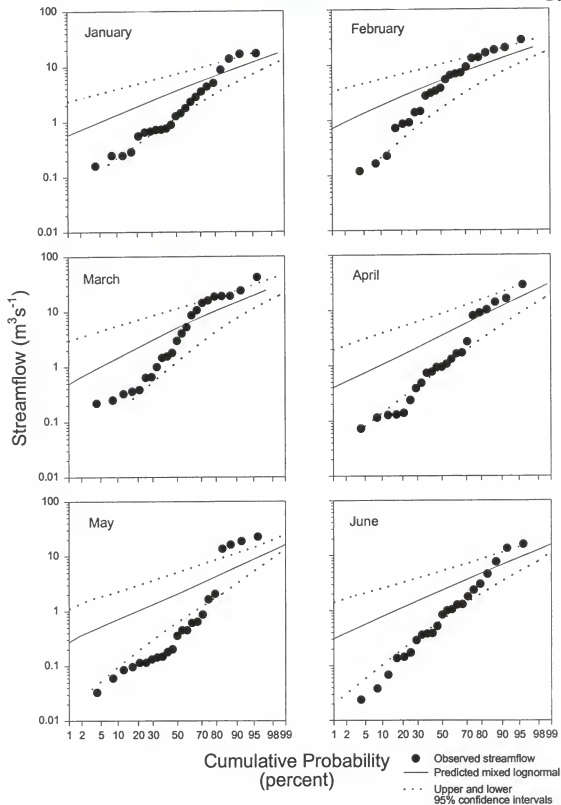


Figure 7.19 Predicted mixed lognormal distribution and confidence intervals, New River

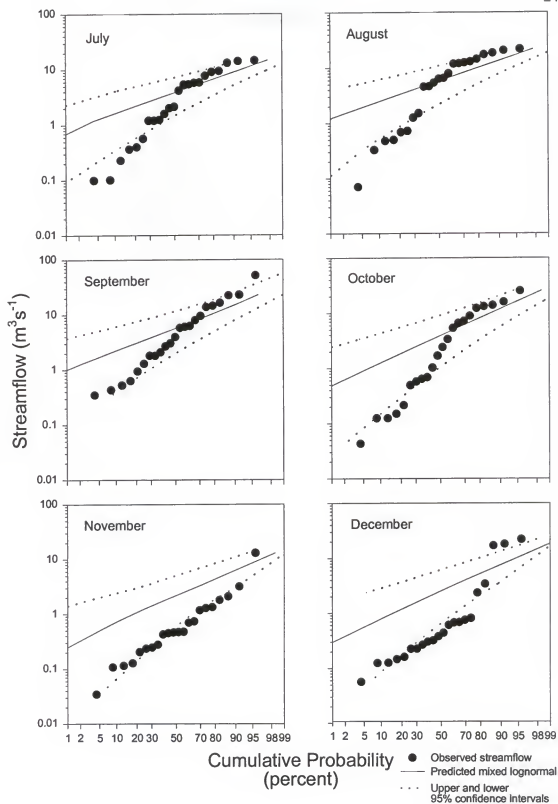


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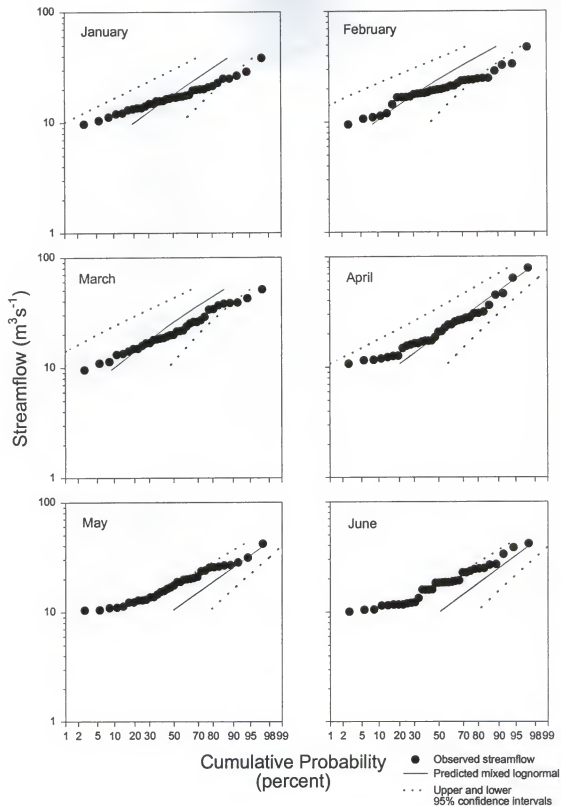


Figure 7.20 Predicted mixed lognormal distribution and confidence intervals, St. Marks

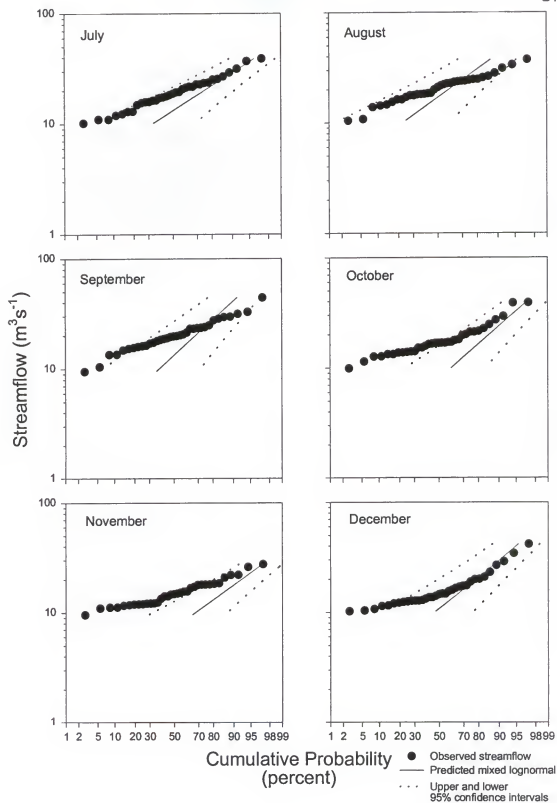


Figure 7.20 -- continued

Concluding Remarks

Second order trend surfaces are shown to provide the most complete spatial representation of the observed model parameters (mean and standard deviation) of the three surfaces tested. Fitted surfaces generally explain the largest variations in each parameter during winter. Results during summer months indicate that the spatial model is better suited to the means than standard deviations.

The ability of the techniques to forecast flow characteristics at ungaged locations is at best mixed, as indicated by the comparison of predicted to observed means at four test stations across northcentral Florida and the subsequent generation of predicted mixed lognormal distributions at these sites for each month. Predictions of means lie within the 90 and 95 percent confidence intervals for most high flow months and are poorer during transition months of low flow. Predictions for one of the four test sites (St. Marks), however, are poor during the entire winter (January-April) high flow period.

Predicted mixed lognormal distributions generally fail to provide adequate fits to the observed flows for most months. By employing parameters extracted from the 95 percent confidence surfaces improvement occurs at two of the

test stations, particularly during the winter high flow season but also to a lesser extent during the summer. The trend surfaces, however, appear to be better descriptive models of monthly streamflow than models by which to generate predictions of flows.

CHAPTER 8 DISCUSSION AND IMPLICATIONS

This chapter provides a general overview of the more salient results presented in previous chapters and a discussion of them within the general framework of the established literature. Contributions that this study has made to the general understanding of river discharge in Florida and the role of ENSO upon it are highlighted as are the weaknesses within the analysis that preclude complete knowledge of the problem. The discussion is centered upon similarities and differences in seasonal and subregional contexts with respect to ENSO, probability distributions and spatial modeling. The final section pertains to potential avenues of further investigation to the problem of modeling streamflow under ENSO conditions.

El Niño/Southern Oscillation

Teleconnections between conditions in the tropical South Pacific and North America, particularly the southeast United States, tend to be strongest during boreal winter and weakest during boreal summer (Webster 1982; Yarnal and

Kiladis 1985; Leathers et al. 1991; Kahya and Dracup 1993a). Qualitatively, results of the analysis indicate that the study area may be subdivided into three hydrologic areas--the panhandle, northcentral and southern regions (figure 8.1). The following discussion is therefore structured according to general observations for winter and summer in these three regions.

Winter

Previous research has suggested that the maximum response in precipitation and streamflow to ENSO occurs across the entire state during the winter following an event (Douglas and Englehart 1981; Ropelewski and Halpert 1986; Hanson and Maul 1991; Kahya and Dracup 1993a,c; Richards 1995). However, this analysis reveals that few stations across the panhandle demonstrate significant associations between mean monthly streamflow and the SOI. In addition there is a general lack of stations that exhibit significant differences in either means or variances in flow between warm and cold events, further indicating that the response across the panhandle is unlike that previously thought. It is well-documented that, during warm events, the subtropical jet stream advects moisture and its attendant precipitation across the entire study area (Rasmusson and Wallace 1983; Lau and Lim 1984; Emery and Hamilton 1985; Yarnal 1985).

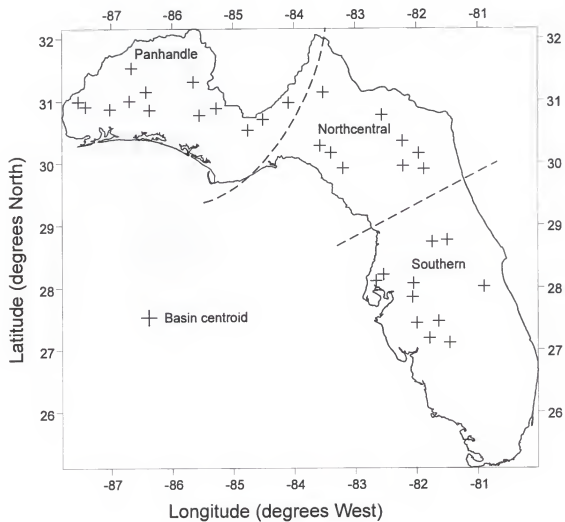


Figure 8.1 Regions of response to ENSO

During cold events it has been proposed that the weakening of the subtropical jet stream, in conjunction with a poleward displacement of the polar jet, produces below average winter precipitation and streamflow (Ropelewski and Halpert 1989; Kahya and Dracup 1993c; Yin 1994). Rather than a poleward displacement of the polar jet, a westward displacement has been proposed by Henderson and Robinson (1994). Such a displacement may provide a physical basis for the similarities in flows across the panhandle during both warm and cold events (Hardy 1996).

Significant negative correlations between the SOI and streamflow across peninsular Florida from January-April support Douglas and Englehart's (1981) assertion that this region displays the greatest negative association between autumnal precipitation across the central equatorial Pacific and subsequent winter precipitation (Douglas and Englehart 1981). This has been put forth as the typical ENSO/streamflow relationship throughout the southeast U.S. (Ropelewski and Halpert 1986, 1989; Kahya and Dracup 1993a,c). However, moisture conditions (represented by the Palmer Drought Severity Index--PDSI) in Florida, which are indicative of available atmospheric water content for the generation of precipitation events, tend to be out of phase with the rest of the southeast (Henry and Dicks 1988; Henry and LeBoutillier 1990). Thus, Florida may be incorrectly

classified as part of the southeast with regard to the effects of ENSO upon precipitation and streamflow.

Significant differences in mean flows between warm and cold events are prevalent throughout the peninsula, especially in northcentral Florida where the pattern is spatially coherent from December-April. These observations support results from the correlation analysis as well as the literature regarding the synoptic processes operating across the region during ENSO conditions (Douglas and Englehart 1981; Ropelewski and Halpert 1986,1989; Kahya and Dracup 1993a,c; Henderson and Robinson 1994).

Summer

A positive relationship between streamflow and SOI exists across north Florida during the summer, particularly during August and September, but its spatial coherency is weaker than that of the winter. This association indicates that streamflow is likely to be below/above average during warm/cold events, supporting Hanson and Maul's (1991) assertion that rainfall is below average across the panhandle during warm event summers (June-August). By contrast, throughout the peninsula rainfall is shown to be above average, which is demonstrated in this analysis of streamflow within northcentral Florida during July. In autumn (September-November) the situation within these

subregions is reversed (Hanson and Maul 1991), supported in this analysis for northcentral Florida but not for the panhandle. Although the spatial coherency is weak, the discrepancies provide further support that the state, as a whole, may not be correctly classified within the larger southeast region.

Comparisons of mean and variance indicate that it is primarily stations in the southern portion of the study area that display differences between warm and cold events. The spatial disposition of these stations reporting differences in variances appears to shift from the south to the north as the summer (July-September) progresses. The small proportion of stations exhibiting this relationship may partially be related to overall weaker summer teleconnections (Yarnal 1985).

The primary summer streamflow generating mechanisms are convection and tropical systems (Jordan 1984; Winsberg 1990). Convictional storms are locally isolated events of relatively short duration and their occurrence is in part related to antecedent moisture conditions (Yin 1994). Tropical systems, however, have a greater areal extent and they are capable of producing copious precipitation (Neumann et al. 1987). They develop more frequently throughout the North Atlantic Ocean basin during cold events (Gray 1984) as does their potential to affect Floridan streamflow. This

research presents the hypothesis that differences in variance between warm and cold years are likely to be present during the tropical storm "season" (particularly the August-October peak) across the panhandle and southern regions which experience the greatest frequency of storm tracks. Although no definitive conclusions may be drawn, evidence to support the assertion is found within northcentral Florida (Zorn and Waylen 1997) and in the predictions of mixed lognormal functions of the test stations in this analysis. Specifically, the estimate of standard deviation appears to be more crucial than that of the mean.

Theoretical Probability Distributions

Identifying an appropriate underlying probability distribution of monthly streamflows enables all flows at a station to be characterized in terms of chance or risk of occurrence (Haan 1977). Four probability distributions--normal, lognormal, gamma and Weibull--are tested for fit, all of which have been suggested as candidate models of monthly flows in previous analyses (Singh and Lonquist 1974; Stedinger 1980; Bras et al. 1983; Richards 1995; Eltahir 1996). The lognormal model is shown to be generally the most appropriate across the study region in all months.

During the winter season it performs less satisfactorily across northcentral Florida, and during the summer it is less appropriate across the panhandle. When the lognormal performs poorly across the panhandle, the general trend is that none of the hypothesized functions adequately models the flows. Furthermore, if any of the four theoretical distributions is applicable to the panhandle, it is usually the lognormal. These spatial contrasts between seasons across the panhandle, northcentral and southern regions reinforce the notion that Florida possesses a fairly heterogeneous set of hydrologic regimes which exhibit complex interannual variability.

Based on the demonstrated effects of ENSO, the mixed lognormal distribution, employing the parameters mean and standard deviation in each of the warm, cold and non-ENSO subsamples, provides a general improvement in fit during the winter, the season of greatest ENSO effect. The model also improves spatial coverage during summer, particularly in the panhandle, one of the areas most sensitive to changes in tropical storm activity. These results support the notions that 1) ENSO affects streamflow across the study area, 2) the effects vary in differing regions and seasons and 3) these flows may be adequately modeled given the occurrence of warm, cold or non-ENSO conditions.

Alternate models including three-parameter forms of the lognormal and gamma distributions exist (Stedinger 1980; Singh 1992), but their application requires the estimation of the third moment (skewness), which tends to be highly unstable. Available historic records of between 30 and 67 years are much smaller than the recommended 100 for reliable estimates of skew (Haan 1977; Griffith and Amrhein 1991).

Modeling Streamflow Across the Study Area

Second order trend surfaces provide significant fits to mean runoff in all months under warm, cold and non-ENSO conditions. The variation in the parameter explained by these surfaces is greatest (generally 80 percent) from November-May, which encompasses the entire winter flow regime. Surfaces of similar order also model the standard deviation of runoff in at least ten months under any set of atmosphere/ocean conditions in the Pacific. The explained variation is greatest during the winter months (generally between 50-80 percent); however, the figure is lower in all months and under all conditions than for the mean.

Spatial comparisons between observed means and standard deviations of runoff show that, in general, the former tend to vary more smoothly across the study region than the latter during both winter and summer. Because trend surface

models are appropriate to data that vary regularly and systematically over space, they are able to account for fairly large percentages in variation of mean streamflows in this analysis (Marsal 1987). By contrast, the more chaotic or random spatial nature of standard deviations renders the trend surface model less able to account for as much variation in the parameter.

The seasonal contrasts in the spatial patterns of both mean and standard deviation of streamflows, and the modeling of the parameters by trend surfaces, are linked with the seasonal precipitation generating mechanisms that produce the flows. During winter the primary generating mechanisms include frontal convergence, due to the southward movement of the polar jet stream from higher latitudes, and advection of tropical moisture from the subtropical branch of the jet stream (Rasmusson and Wallace 1983; Lau and Lim 1984; Yarnal 1985; Ropelewski and Halpert 1986, 1989; Kahya and Dracup 1993a,c; Henderson and Robinson 1994; Hardy 1996). Regardless of climatic differentiation based upon ENSO, the mechanisms tend to operate at a regional scale (Rasmusson and Wallace 1983; Ropelewski and Halpert 1986; Henderson and Robinson 1994). Streamflow therefore tends to vary systematically across the study area; thus 2nd order trend surfaces are able to not only satisfactorily model the flows, but they account for much of the variation in them.

By contrast, convective thunderstorm activity, in conjunction with the occasional tropical storm or hurricane, generates the majority of runoff during summer (Jordan 1984; Winsberg 1990; Hanson and Maul 1991). Operating at a more local scale than polar fronts and jet streams, these processes produce more random patterns of streamflow across the study region. Although 2nd order trend surfaces are in general able to satisfactorily model these flows, the variation explained by them is reduced due to the inherent nature of the physical processes.

Prediction

In general, the fit of the mixed lognormal probability distributions of flows based on predictions of parameters from the fitted surfaces are poor. Again, there is a seasonal component to the efficacy of the procedure whereby predicted distributions are better during winter months, particularly February and March, when the effects of ENSO upon the study region are at a maximum (Webster 1982; Yarnal 1985; Ropelewski and Halpert 1986, 1989; Kahya and Dracup 1993a,c; Henderson and Robinson 1994). Inspection of estimates from the 95 percent confidence surfaces suggest that accurate estimation of the mean is more important than that of the standard deviation during this season,

supporting the notion that differences in mean streamflows between warm and cold conditions are likely to be significant during winter. Although the results are not as good during the summer, adequate probability distributions are predicted during August and September. In contrast to winter months, evidence suggests that it is the estimate of standard deviation (variance) that is more crucial to the adequate prediction of the distribution at this time of year. This lends support to the idea that differences in variance between warm and cold conditions are more noticeable during summer months, and that Florida is incorrectly classified within the broader southeast region.

General Discussion

Demonstrated effects of ENSO upon mean monthly streamflow are established by this research. The presence of a winter response, noted within the literature, is both substantiated and refuted. Runoff tends to be above average during warm events and below average during cold events. However, this analysis offers evidence opposing the general classification of Florida rivers within the larger southeast U.S. region, as suggested by the literature (Douglas and Englehart 1981; Ropelewski and Halpert 1986,1989; Kahya and Dracup 1993a,c). The panhandle and northcentral subregions

display differing responses from other regions primarily during winter and summer, respectively.

Trend surface analysis provides adequate representation of mean flows and their standard deviations with only a few exceptions. The poorer fits are generally confined to summer and autumnal transition periods. Reasons for this include the local nature of the physical processes generating streamflow and the random or chaotic nature in the spatial distribution of standard deviations during these months. Regarding the latter, 3rd order surfaces provide no better fits (and in many cases poorer fits) to the standard deviations, thereby confirming the "noisy" signal present at the monthly scale. Seasonal aggregation of flows may provide a viable alternative to monthly data.

The greatest difficulty with respect to generating adequate predictions of mixed probability distributions at the four test stations appears to be poor estimates of standard deviation. Sample size provides one reason for this persistent problem. Although the periods of record from the calibration stations are greater than 30 years, their division into subsamples based upon warm, cold and non-ENSO conditions effectively reduces each sample, making parameter estimation of second moments very sensitive to outliers. Because calculating the statistic necessitates

squaring differences about the mean, outliers greatly inflate results (Stedinger 1980; Burt and Barber 1996).

Concluding Remarks

An overview of the more significant results are addressed within the context of the literature regarding ENSO, probability distributions and spatial modeling. This analysis contributes to the overall understanding of the effects of ENSO upon streamflow in Florida, which is presented temporally within a seasonal (winter and summer) framework and spatially across three qualitative hydrologic units--the panhandle, northcentral and southern regions.

Mean monthly streamflows and their standard deviations are modeled successfully via second order trend surfaces for most months and climatic conditions. Furthermore, the surfaces of each climatic condition explain over 80 and between 50-80 percent of the variation in means and standard deviations, respectively, during most winter months. Although the percentage of variation explained is lower during the summer, the technique is still generally applicable.

Prediction of mixed lognormal distributions, by which to model the monthly flows of four test gaging stations in northcentral Florida, is more successful during winter

months than in summer. Estimates of mean and standard deviation employed from the 95 percent confidence surfaces indicate that the means are more important during winter while standard deviations are more important during summer.

CHAPTER 9 CONCLUSION

The effects of ENSO upon monthly streamflow across Florida are demonstrated within this dissertation through the use of statistical techniques that reveal the complexities within the temporal and spatial patterns of association. The analysis provides previously undocumented conclusions drawn from the amalgamation of different academic perspectives. The novel geographic and temporal observations are well grounded in techniques of quantitative modeling and are justifiable and supportable in the context of contemporary hydrologic and climatologic knowledge.

Geography

Florida has previously been identified as a subregion of homogeneous response to ENSO in precipitation and streamflow both temporally (primarily winter and spring) and spatially, similar to that of the entire southeast United States. However, this research indicates that Florida streamflow responds in fairly complex ways to ENSO, largely due to its peninsular nature which produces contrasts

between the north and south. In particular, the analysis identifies three regions of differing response to ENSO--the panhandle, northcentral and southern regions--marked by variations between winter and summer months.

It has previously been proposed that both winter precipitation and streamflow are above/below average under warm/cold ENSO conditions throughout the state. The present analysis demonstrates that mean streamflow across the panhandle, during these months, is generally not significantly different between warm and cold events, unlike peninsular Florida. The interannual variance in these flows between warm and cold events, which is previously unidentified, is most pronounced across northern Florida, although the southern region also demonstrates a degree of similarity, briefly, in the early part of the season.

No relationship between summer streamflow and ENSO had previously been identified in the literature. However, mean flows across the panhandle tend to be below/above average during warm/cold events. This association becomes less clear in northcentral Florida. Flows appear to respond in an opposing fashion to those of the panhandle at the outset of the high flow season (July), but similarly during the remaining months. Differences in the variance of streamflow are most pronounced in the southern region in July. A spatial shift in the response of this parameter occurs

northwards as the summer progresses. The processes generating these subregional and seasonal variations in response are closely linked to hypothesized climatic and hydrologic controls operating during ENSO events.

Hydrology and Climatology

Synoptic processes governing winter precipitation and subsequent streamflow include the average seasonal position and strength of the polar and subtropical jet streams. During cold events the former is reported to be located to the north of Florida and the latter to be weak and spatially incoherent, producing below average precipitation and streamflow. However, this analysis supports recent assertions that the polar jet is actually displaced westward during cold events. The implication is that the panhandle (particularly the western section) remains under the influence of the polar jet under either condition and experiences little difference in mean monthly flows between warm and cold events as distinct from the peninsula. During warm events the polar jet combines with the persistent subtropical branch across the entire study area, resulting in above average precipitation and streamflow. Due to its northern location, northcentral Florida experiences these effects over the greatest period.

During summer, the principle controls of moisture are the strength and position of the North Atlantic anticyclone (Bermuda High pressure cell). Its seasonal strengthening, partially in response to the intense heating of the landmass across the southeast, results in the advection of warm, moist, unstable air across the region. Increasing water temperatures of the Gulf of Mexico and Atlantic Ocean provide large sources of energy for the development of both convective and tropical storms. Seasonal effects of ENSO upon the region are poorly documented, in part because teleconnections between the tropical South Pacific and the southeast U.S. are the weakest during summer. However, research indicates that tropical cyclones develop more frequently throughout the North Atlantic during cold events. This dissertation demonstrates some differences in runoff during months corresponding to the early peak period of storm occurrence. In the southern region differences in both mean and variance are apparent, particularly during mid-summer (July and August), while in northcentral Florida the effects are most noticeable in the variances of flows between warm and cold events.

Ramifications of these conclusions are directly related to issues involving water resources in the state. Seasonal forecasts of ENSO conditions, now generally reliably provided by NOAA and other agencies, could be employed in

conjunction with results of this research to provide information pertaining to both anticipated absolute volumes of streamflow and their likely variabilities for winter and summer months. One of the more salient aspects of this research pertains to the modeling of the variances of flow, which suggests that variations are larger during cold years. The enhancement of variance in streamflows may result from non-linear feedbacks in the hydrologic system through which interannual variability in precipitation may be amplified by such factors as evapotranspiration and convection. The demand for water, losses of surface water to evapotranspiration, and the variability in streamflow between warm and cold ENSO conditions, are the greatest during summer and thus have strong practical implications for the management of water resources.

Quantitative Modeling

The representation and quantification of the variability in streamflow is achieved through the use of frequency distributions, standard parametric statistics and trend surface analysis. The statistical methods are appropriate, based upon a physical understanding of seasonal streamflow generating processes, and easily and ubiquitously applied throughout the state.

The lognormal probability distribution, identified as most suitable for modeling the monthly flows, successfully represents the range of runoffs during warm, cold and non-ENSO climatic conditions and, in a mixture model, their combination. Not only does the mixture model provide a more catholic spatial coverage than the undifferentiated model, but its improvement is most notably during these seasons when the influence of ENSO is greatest.

Parameters of the mixed lognormal distribution are modeled successfully via second order trend surfaces which account for much of the spatial variation in both means and standard deviations. This is particularly true during winter months when regional scale frontal activity is the dominant generating process. The decrease in explained variance in each parameter during summer months reflects the generally more localized nature of the streamflow generating processes in these months.

Finally, the ability to estimate distribution parameters at ungaged basins from these surfaces is better during winter and somewhat marginal during summer. Estimates extracted from the confidence surfaces once again indicate that the mean is more important during winter while that of standard deviation (variance) is more important during summer.

Concluding Remarks

In summary, a suitable probabilistic modeling technique is developed to represent mean monthly flows spatially across Florida. The model provides a method for summarizing all flows with only two parameters, mean and standard deviation, under warm, cold and non-ENSO climatic conditions. The techniques employed contribute to the understanding of the effects of ENSO upon streamflow in previously unidentified ways. Incorporation of the variability in flows provides additional physical insights and allows the frequency characteristics to be represented in greater detail than previous analyses which have focused solely upon the mean. The parameters are successfully modeled across the study area, maintaining links between the statistics and both local and regional hydrometeorologic streamflow generating processes. Finally, the analysis demonstrates that effects of ENSO upon monthly streamflow are more seasonally and spatially complex than previously thought.

APPENDIX A
STREAMFLOW GAGING STATIONS

Station Name, Location	Sta #	Basin centroid	
		Lat. (°N)	Long. (°W)
Joshua Creek at Nocatee	2297100	27.19	81.79
Horse Creek near Arcadia	2297310	27.43	82.00
Alafia River at Lithia	2301500	27.85	82.06
Blackwater Creek near Knights	2302500	28.07	82.05
Brooker Creek near Tarpon Springs	2307359	28.11	82.66
Anclote River near Elfers	2310000	28.21	82.54
Suwannee River at White Springs	2315500	30.77	82.57
Withlacoochee River near Pinetta	2319000	31.14	83.53
Santa Fe River at Worthington Springs	2321500	29.95	82.37
Steinhatchee River near Cross City	2324000	29.91	83.20
Fenholloway River near Foley	2324400	30.16	83.40
Econfina River near Perry	2326000	30.28	83.58
Ochlockonee River near Havana	2329000	30.97	84.09
Little River near Quincy	2329500	30.70	84.51
Telogia Creek near Bristol	2330100	30.53	84.76
Chipola River near Altha	2359000	30.88	85.28
Choctawhatchee River at Caryville	2365500	31.31	85.65
Holmes Creek at Vernon	2366000	30.77	85.55
Yellow River at Milligan	2368000	31.15	86.43
Shoal River near Crestview	2369000	30.82	86.37
Blackwater River near Baker	2370000	31.00	86.70
Big Coldwater Creek near Milton	2370500	30.87	87.02
Escambia River near Century	2375500	31.53	86.67
Pine Barren Creek near Barth	2376000	30.91	87.42
Brushy Creek near Walnut Hill	2376300	30.99	87.54
St. Mary's River near Macclenny	2231000	30.35	82.23
St. John's River near Christmas	2232500	28.02	80.88
Wekiva River near Sanford	2235000	28.76	81.50
Ocklawaha River near Conner	2240000	28.76	81.78
S. Fork Black Creek near Penney Farms	2245500	29.90	81.88
N. Fork Black Creek near Middleburg	2246000	30.12	81.96
Fisheating Creek at Palmdale	2256500	27.11	81.46
Charlie Creek near Gardner	2296500	27.46	81.64

Station Name, Location	Sta #	Gaging station	
		Lat. (°N)	Long. (°W)
Joshua Creek at Nocatee	2297100	27.17	81.88
Horse Creek near Arcadia	2297310	27.20	81.99
Alafia River at Lithia	2301500	27.87	82.21
Blackwater Creek near Knights	2302500	28.14	82.15
Brooker Creek near Tarpon Springs	2307359	28.10	82.69
Anclote River near Elfers	2310000	28.21	82.67
Suwannee River at White Springs	2315500	30.33	82.74
Withlacoochee River near Pinetta	2319000	30.60	82.26
Santa Fe River at Worthington Springs	2321500	29.92	82.33
Steinhatchee River near Cross City	2324000	29.79	83.32
Fenholloway River near Foley	2324400	30.10	83.47
Econfina River near Perry	2326000	30.17	83.82
Ochlockonee River near Havana	2329000	30.55	84.38
Little River near Quincy	2329500	30.59	84.50
Telogia Creek near Bristol	2330100	30.43	84.93
Chipola River near Altha	2359000	30.53	85.17
Choctawhatchee River at Caryville	2365500	30.78	85.83
Holmes Creek at Vernon	2366000	30.63	85.71
Yellow River at Milligan	2368000	30.75	86.63
Shoal River near Crestview	2369000	30.70	86.57
Blackwater River near Baker	2370000	30.83	86.73
Big Coldwater Creek near Milton	2370500	30.71	86.97
Escambia River near Century	2375500	30.97	85.23
Pine Barren Creek near Barth	2376000	30.80	87.37
Brushy Creek near Walnut Hill	2376300	30.89	87.54
St. Mary's River near Macclenny	2231000	30.36	82.08
St. John's River near Christmas	2232500	28.54	80.94
Wekiva River near Sanford	2235000	28.82	81.42
Ocklawaha River near Conner	2240000	29.21	81.99
S. Fork Black Creek near Penney Farms	2245500	29.98	81.85
N. Fork Black Creek near Middleburg	2246000	30.11	81.91
Fisheating Creek at Palmdale	2256500	26.93	81.32
Charlie Creek near Gardner	2296500	27.37	81.80

Station Name, Location	Sta #	Basin Area (km ²)	Period of Record (years)
Joshua Creek at Nocatee	2297100	341.9	43
Horse Creek near Arcadia	2297310	564.6	43
Alafia River at Lithia	2301500	867.7	60
Blackwater Creek near Knights	2302500	284.9	42
Brooker Creek near Tarpon Springs	2307359	77.7	43
Anclote River near Elfers	2310000	187.8	47
Suwannee River at White Springs	2315500	6293.7	69
Withlacoochee River near Pinetta	2319000	5490.8	61
Santa Fe River at Worthington Springs	2321500	1489.3	61
Steinhatchee River near Cross City	2324000	906.5	43
Fenholloway River near Foley	2324400	155.4	37
Econfina River near Perry	2326000	512.8	43
Ochlocknee River near Havana	2329000	2952.6	67
Little River near Quincy	2329500	613.8	42
Telogia Creek near Bristol	2330100	326.3	42
Chipola River near Altha	2359000	2022.8	61
Choctawhatchee River at Caryville	2365500	9062.4	63
Holmes Creek at Vernon	2366000	999.7	32
Yellow River at Milligan	2368000	1616.2	55
Shoal River near Crestview	2369000	1227.7	55
Blackwater River near Baker	2370000	531.0	43
Big Coldwater Creek near Milton	2370500	613.8	53
Escambia River near Century	2375500	9886.0	58
Pine Barren Creek near Barth	2376000	195.0	40
Brushy Creek near Walnut Hill	2376300	126.9	34
St. Mary's River near Macclenny	2231000	1813.0	66
St. John's River near Christmas	2232500	3986.0	59
Wekiva River near Sanford	2235000	489.5	56
Ocklawaha River near Conner	2240000	3097.6	31
S. Fork Black Creek near Penney Farms	2245500	347.1	52
N. Fork Black Creek near Middleburg	2246000	458.4	60
Fisheating Creek at Palmdale	2256500	805.5	61
Charlie Creek near Gardner	2296500	854.7	43

APPENDIX B
STANDARDIZED RESIDUALS AND PREDICTED RUNOFF

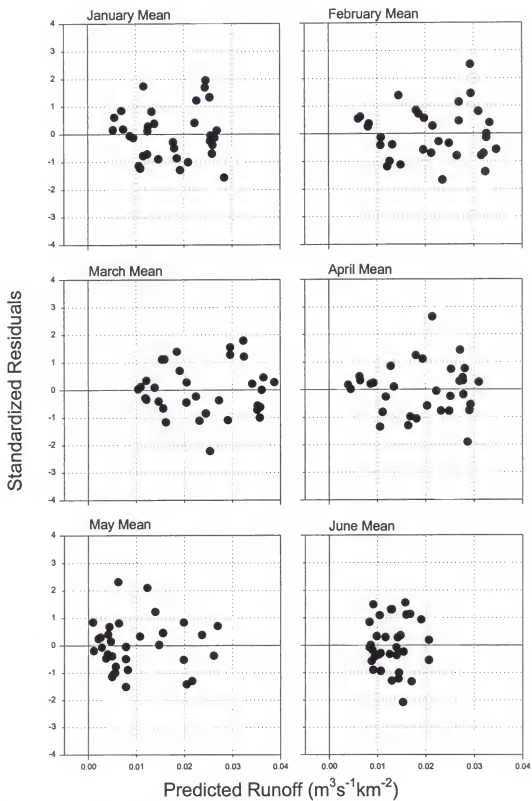


Figure B.1 Residuals of mean, warm years

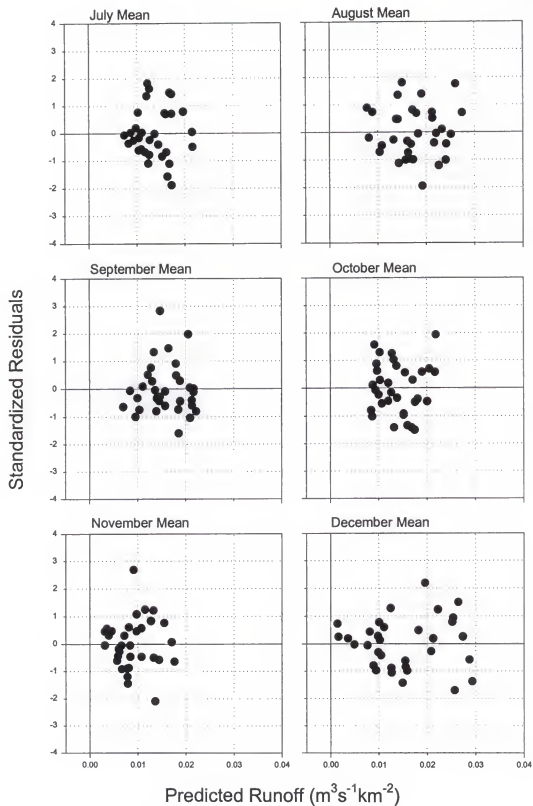


Figure B.1 -- continued

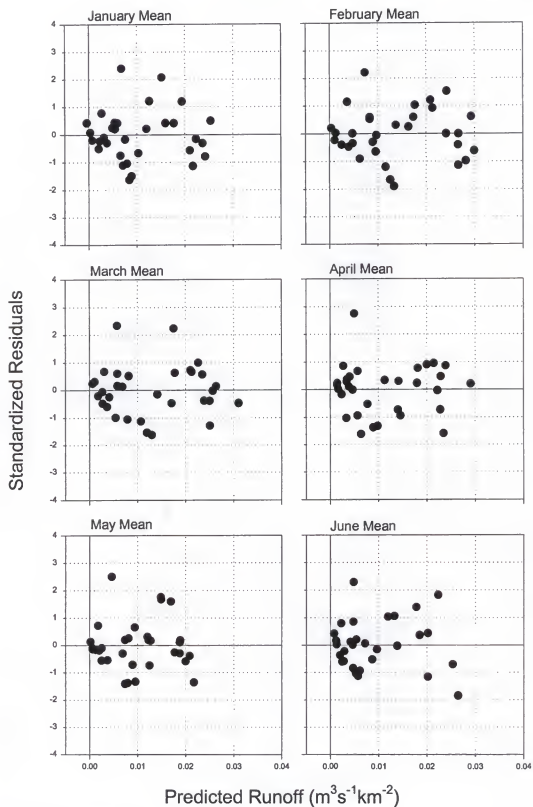


Figure B.2 Residuals of mean, cold years

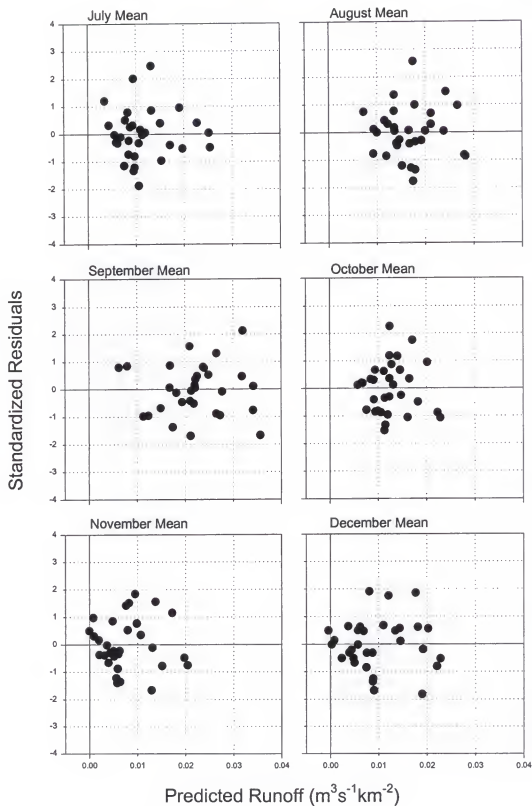


Figure B.2 -- continued

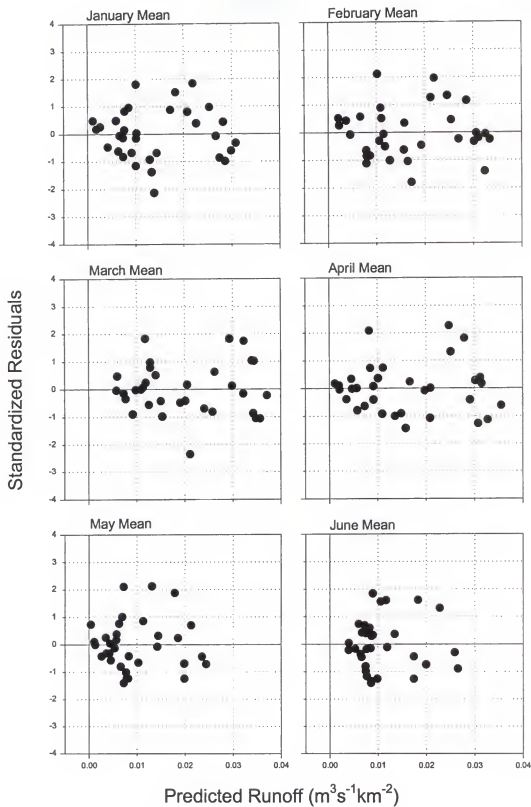


Figure B.3 Residuals of mean, non-ENSO years

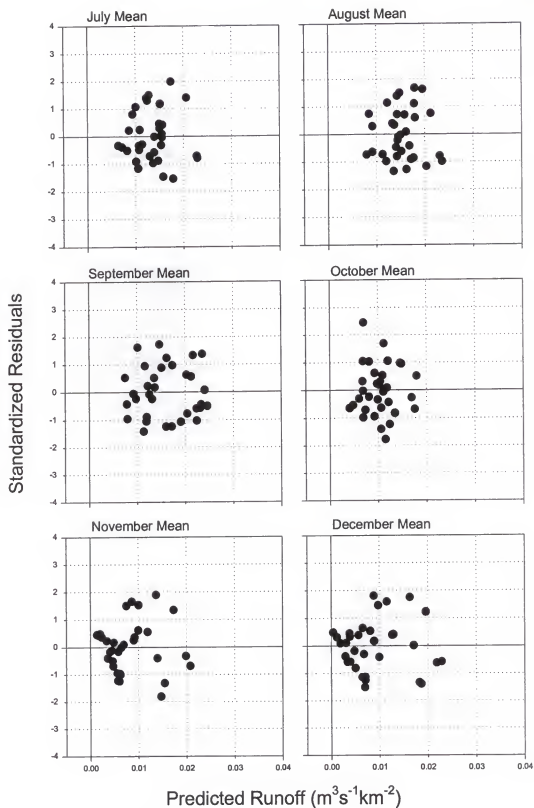


Figure B.3 -- continued

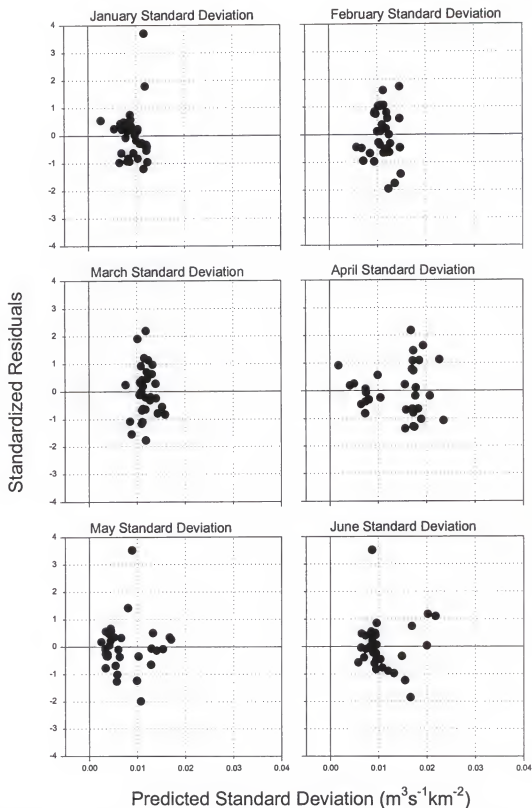


Figure B.4 Residuals of standard deviation, warm years

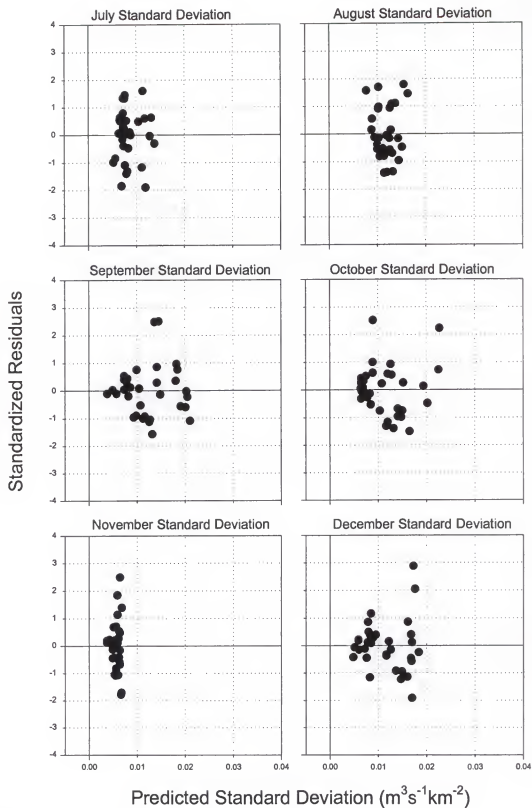


Figure B.4 -- continued

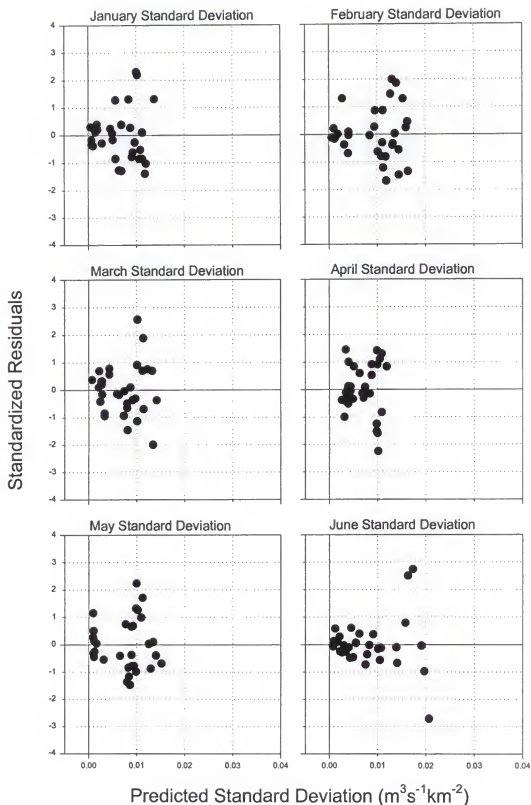


Figure B.5 Residuals of standard deviation, cold years

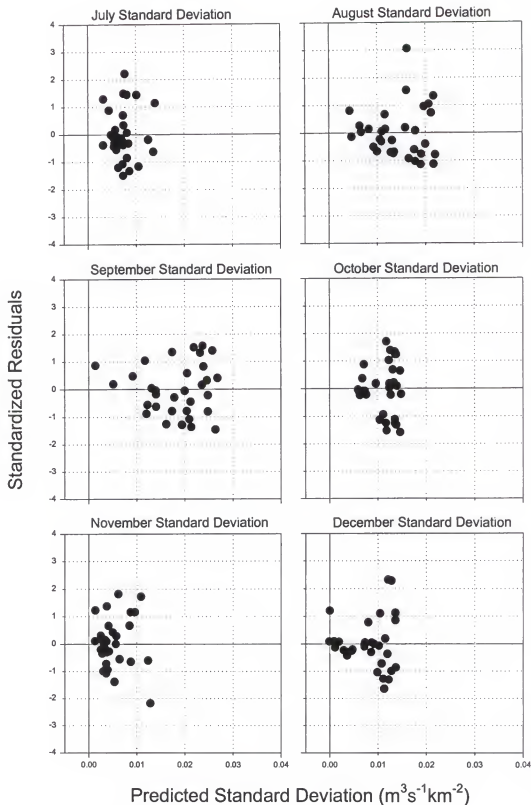


Figure B.5 -- continued

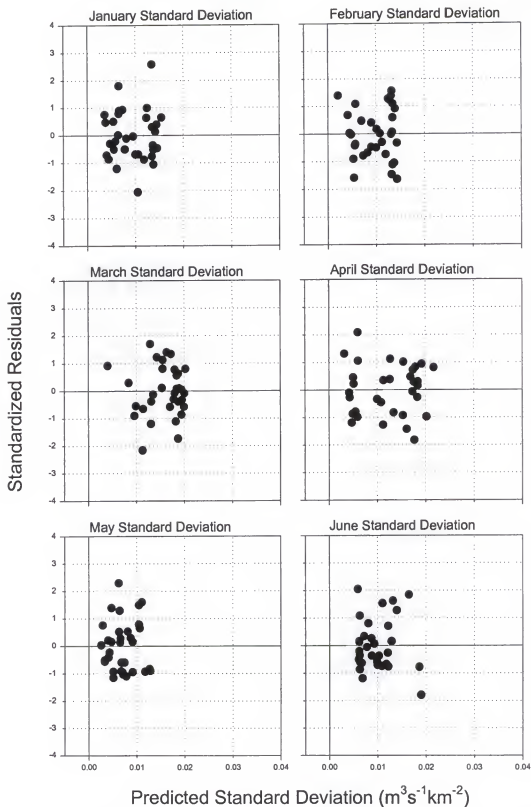


Figure B.6 Residuals of standard deviation, non-ENSO years

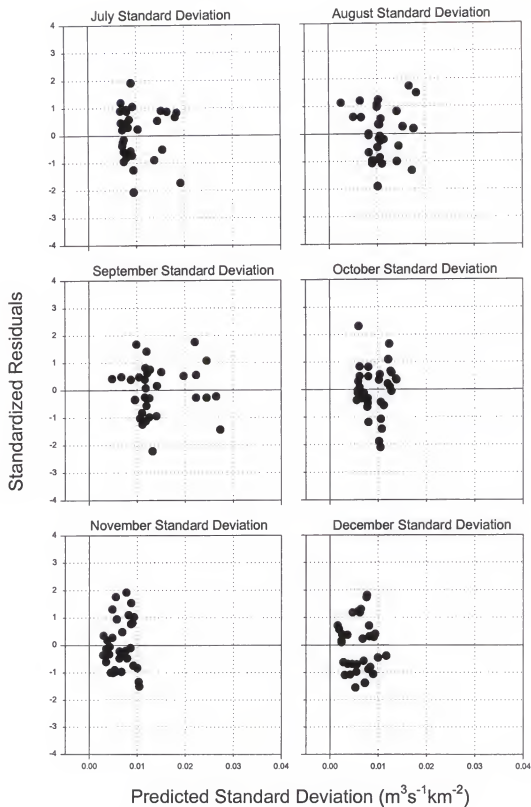


Figure B.6 -- continued

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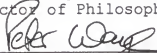
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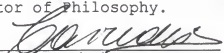
BIOGRAPHICAL SKETCH

Matthew Robert Zorn was born in Greensboro, North Carolina, on July 18, 1961. He received his primary and secondary education in Hickory, North Carolina. Married in 1984, he and his wife moved to Boone, North Carolina, where he received a bachelor's degree in interdisciplinary studies from Appalachian State University in 1986. He worked as a park ranger for the National Park Service (Blue Ridge Parkway) from 1987-1989 and he earned his second undergraduate degree, in geography, from Appalachian State in 1989. In 1991 he was awarded the Master of Arts degree in geography from Appalachian State, after which he taught as a visiting instructor at West Georgia College in Carrollton, Georgia, for one year. He then came to the University of Florida in 1992 to pursue a doctorate degree where his major coursework is in geography and his minor is in geology.

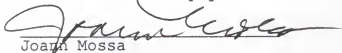
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Peter R. Waylen, Chair
Professor of Geography

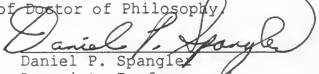
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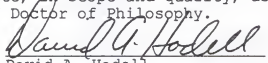
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This dissertation was submitted to the Graduate Faculty of the Department of Geography in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August, 1997

Dean, Graduate School